Charge distribution and charge correlation in the annihilation of antiprotons on nuclei

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A schematic model is devised to account for the charged track pattern in antiproton nucleus annihilation at low momenta. The ejection mechanism is assumed to correspond to a clan picture, where the ancestors are pions. Good agreement is obtained for multiplicity distributions, in neon and in emulsion, and in particular for the very strong correlation observed in neon between negative pions and the total number of charged tracks.

I. INTRODUCTION

Experiments at the Low Energy Antiproton Ring (LEAR) at CERN on antiproton annihilation on nuclei have shown[1] that proton and pion cross sections are grossly consistent with the following simple picture: The antiproton annihilates on a single nucleon, producing a few pions. Some of them travel through the nucleus, ejecting nucleons. They may also be absorbed. This scheme has been embodied in a very elaborated form by the intranuclear cascade (INC) model.[2,3] The latter successfully reproduces the inclusive proton, pion, neutron,[4] fission yields, and the distribution of the residual nuclei,[5] when supplemented by an evaporation model.[6] Streamer chamber and emulsion experiments have recently been analyzed. They provide charged particle multiplicities[7,8] resulting from annihilation. Here we want to analyze these data with a simple model which retains the basic premises of the INC but which is free of its complicated space-time structure that, we think, is not important for charged track multiplicities. It is therefore much more transparent, requires small computational effort and handles charge conservation exactly at each step (in contradistinction with the present status of the INC code of Ref. 3, which disregards isospin degrees of freedom).

We obtain a good description of the charged track multiplicities and a clear interpretation of the correlation observed in $\bar{p}$-Ne between the number of negative pions and the total number of charged tracks M.

II. A SIMPLE PICTURE FOR THE PRODUCTION OF CHARGED TRACKS

In Ref. 9, the distribution of multiplicity of charged tracks in $\bar{p}$ annihilation in emulsion has been fitted by negative binomial (NB) shapes. This was interpreted as an indication of a compound distribution:[9,10] A first generation of primary objects (called ancestors) giving rise to clans of secondary products. It is known that a NB is obtained when the first generation follows a Poisson law and the second one a logarithmic law. Although the idea of clan structure is very appealing, the analysis of Ref. 9 is physically unsatisfactory in two respects: (a) the number of ancestors is found larger than the number of interacting pions, which are the natural candidates for the ancestors; (b) a clan with zero prong is excluded from the analysis. Here we investigate a model based on another compound distribution. We identify the ancestors with the pion issued from the $\bar{p}$ annihilation, which interact with the target nucleons. We assume that they follow a Poisson distribution. This is confirmed by recent INC calculations[3,6] (although the total number of pions follows a Gaussian law), from where we extract the value of the average number of interacting pions. Actually, we verified that the distribution of the ejected nucleons N_{ej} in the INC of Ref. 6 follows a compound Poisson distribution (although multivariate distributions may be very similar,[11] we found that a peak at $N_{ej}=0$ is characteristic of a compound Poisson distribution); see Fig. 1. This greatly suggests that the INC dynamics (for particle ejection at least) can be compactly summarized as follows: (1) the number of interacting pions is Poissonian; (2) each of them initiates a cascade (pion streak) through the nucleus, describable in terms of mean-free path. On this basis, we propose a simple model for charged track production. It retains the cited features and has some refinements added: (1) the distinction between the charges for pions and for nucleons; (2) the possible absorption of pions; (3) the depletion of the target by successive collisions.

III. INGREDIENTS OF THE MODEL

The model treats the particle emission as the result of pion propagation with stochastic properties. A definite ordering is assumed, allowing to take into account charge conservation at any vertex. The scheme is sketched in Fig. 2. The model is studied by simulation. Each run of a nuclear event ends up with a definite number of positive, neutral, and negative pions as well as ejected protons and neutrons (or alpha particle, see below). The structure of charge emission is registered to build up the multiplicity distributions and correlations. We now give some details of the procedure.

Interacting pions. The nucleon which annihilates with the antiproton is chosen to be a proton or a neutron with respective probability Z/A and $(A-Z)/A$, where A and Z are the mass and charge number of the target. The number and charge of the produced pions are determined according to the statistical model of Ref. 12, which pro-

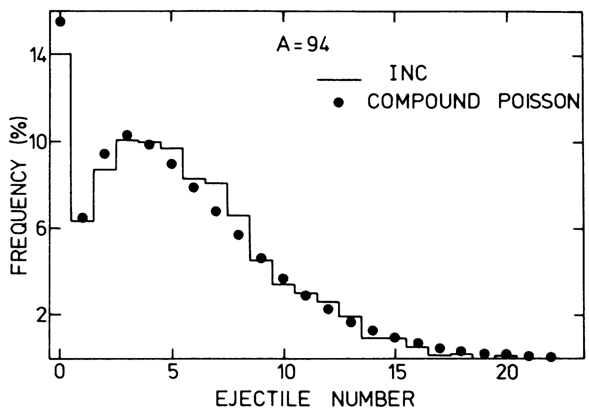

FIG. 1. Multiplicity distribution of the nucleons ejected in the cascade up to $t=50$ fm/c (histogram) compared to a compound Poisson shape (points). The mean value of the number of interacting pions is 2.04 and the mean number of ejectile per interacting pion is 2.49. The figure refers to annihilation at rest on mass 94 target.

vides a good description of the pion distribution in $\bar{p}p$ and $\bar{p}n$. The interacting pions are selected by a stochastic procedure which reproduces the distribution obtained in the INC. The fraction of interacting pions turns out to be 0.6 for the annihilation in flight irrespective of $\bar{p}$ momentum.

Pion streaks. We assume that the streaks are independent of each other (see below, however) and that the number of ejective collisions, i.e., those which lead to the emission of a nucleon from the nucleus, follows a Poisson law, with mean $\bar{n}$.

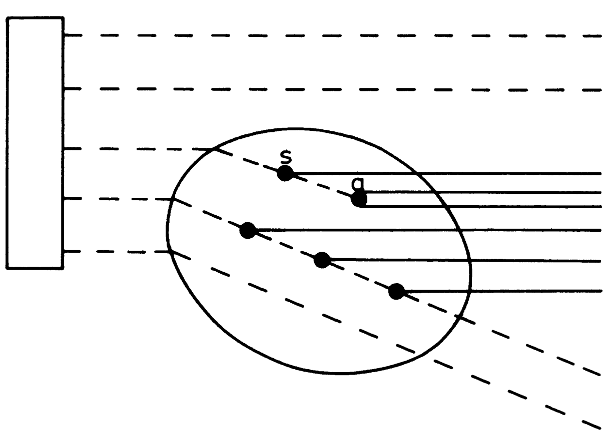

FIG. 2. Schematic picture of the model mechanism. The horizontal direction corresponds to time flow. The rectangular zone represents the initial $\bar{p}$-nucleon annihilation. The pions (dashed lines) either leave the nucleus without interacting strongly (the two upper lines) or interact. The interactions are included in the oval zone. Nucleons (continuous lines) are kicked off as a result of pion scattering (vertex of type s) or absorption (vertex of type a). An interacting pion may avoid to eject any nucleon (lower line). The interactions which do not lead to the emission of nucleons are disregarded.

What happens during an ejective collision is pictured in close analogy with the standard cascade:[3]

$$\pi N \to \Delta, \quad \Delta \to N\pi \ . \tag{1}$$

The probability for the target nucleon N being a proton or a neutron is taken to be $P_p = Z/A$ and $P_n = (A-Z)/A$, respectively, where A and Z are the mass and charge numbers of the *actual* residue (which takes into account the depletion of the target). What happens in a streak may thus depend upon the previous history of all the streaks. The streaks are thus correlated by the charge and baryon number conservation, but they are dynamically uncorrelated. In this sense they are independent. The branching ratios for the different final states (in terms of charge) in (1) are calculated within the isobar model.

The average number $\bar{n}$ of ejective collisions is taken to be

$$\bar{n} = aA^b \ , \tag{2}$$

where a and b have been chosen to fit the average multiplicity $\langle M \rangle$ in all cases, independently of the $\bar{p}$ momentum. We stress that a and b are the only free parameters in our analysis, since we fixed all the other ingredients on the INC predictions. [We consider that annihilations in emulsion occur in 72% of the cases on heavy targets ($\bar{A}=94$, $\bar{Z}=41$) and in 28% on light targets ($\bar{A}=14$, $\bar{Z}=7$), following Ref. 7.] For annihilation at rest, however, we were forced to use a somewhat smaller value of $\bar{n}$, in order to get a good fit. This is in keeping with the more peripheral aspect of the annihilation in the latter case.

Pion absorption. We manage the possibility of pion absorption by giving a chance to the pion to be absorbed at the last collision of the emission path. This probability $P_a \sim 0.4$ is chosen to reproduce the pion absorption as predicted by the INC.[3] When absorbed the pion gives rise to the sequence

$$\pi N \to \Delta, \ \Delta N \to NN \ , \tag{3}$$

where the isobar model is again used to determine the various branching ratios. In view of the energy released, the two nucleons are assumed to be ejected. The results are insensitive to reasonable variations of P_a.

Neon target depletion. For neon it appeared that the rather abrupt slope of the distribution in the region of high M values was not well reproduced. This is not surprising. The model described above implicitly assumes, through the idea of constant mean-free path, a not too strong depletion of the target. It becomes unrealistic in some fraction of the events, for low A values of the residue. To cure this feature, we have made the following assumption: When, in the course of the emission sequence either Z or $(A-Z)$ reaches down the value 2, the nucleus is broken down into an alpha particle (forming one track) and remaining nucleons; the pions present at that step do not interact any more. The improvement for the neon data is significant. This may be related to the alpha-cluster structure of ^{20}Ne.[13] The effect for emulsion is small in view of the importance of the heavy components.

In conclusion, we built a model which retains the basic features of the INC, without the complications of the space-time evolution. The input data are fixed on the INC whenever possible. In addition, the isospin degrees of freedom are naturally included. The predictions of the model are obtained by simulation. Forty thousand events at each energy have been produced, which required ~100 s on an IBM 4381 computer.

The work of Ref. 14 also simulates the pion cascades through the nucleus following $\bar{p}$ annihilation. It differs from ours in the sense that it deals with the energy loss and the absorption of the pions, but disregards the evolution of the struck nucleons. It cannot therefore make predictions on the multiplicities.

IV. RESULTS

A. Multiplicity distributions

We have adjusted the model on four M distributions in emulsion and three M distributions in neon at the same time. To fit the multiplicity distributions we need a single set of values for the two parameters of the model [Eq. (2)]; $a = 1.3$, $b = 0.26$. The shapes obtained for the M distributions are compared to the data in Fig. 3 for emulsion and in Fig. 4 for neon. The mean values $\langle M \rangle$ are given in Table I. Our results show a general agreement which is quite satisfactory. The distribution of the negative pion multiplicity, which is available for Ne, is also shown in Fig. 5, and compared to our predictions.

The charged particle multiplicities result from the contribution of the streaks initiated by the interacting pions (whose nucleon component is expected to be close to a compound Poisson as we explained) and the contribution due to the noninteracting charged pions (which are, of course, also detected). It is then remarkable that the addition of the contributions gives rise to a multiplicity distribution with a rather simple shape. Unfortunately, our model, although very simple in its formulation, is already too complicated, due essentially to contribution mixing, to allow us to write down even approximately its predictions in a compact analytical form. Let us finally mention that the agreement between the predictions of our model and the data of Fig. 3 is better than the fit by NB of Ref. 9.

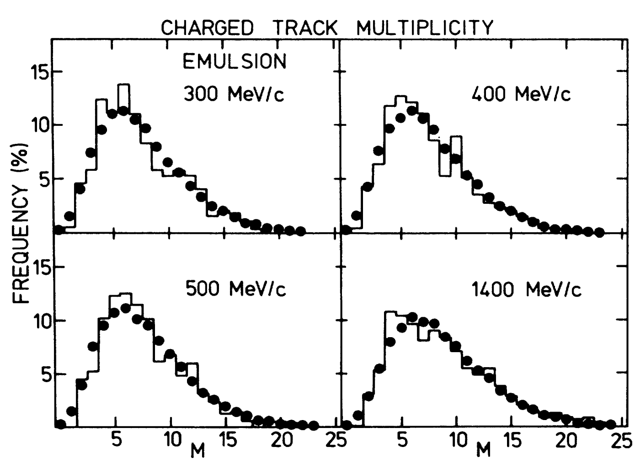

FIG. 3. Multiplicity distribution of charged tracks from $\bar{p}$ annihilations in emulsion. The histograms are the data from Ref. 7. The points are the model results.

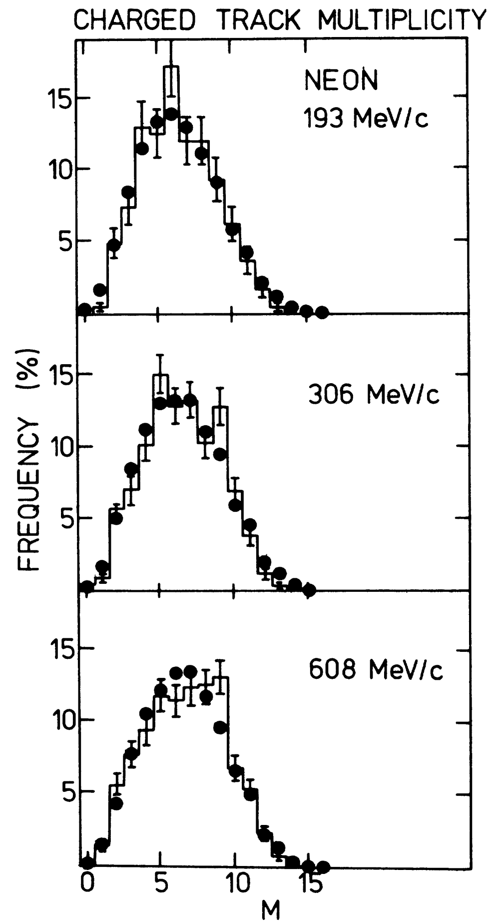

FIG. 4. Multiplicity distribution of charged tracks from $\bar{p}$ annihilation on neon. The histograms are the data from Ref. 8. The points are the model results.

TABLE I. Mean number of charged tracks. The experimental values come from Ref. 7 (emulsion), Refs. 8 and 15 (neon).

$\bar{p}$ momentum (MeV/c)	Experiment	Model
	Emulsion	
at rest	4.9	4.89
300	7.4	7.55
400	7.5	7.59
500	7.6	7.63
1400	8.6	8.45
	Neon	
at rest	5.65±0.3	5.65
193	6.37±0.33	6.41
306	6.43±0.25	6.44
608	6.67±0.24	6.60

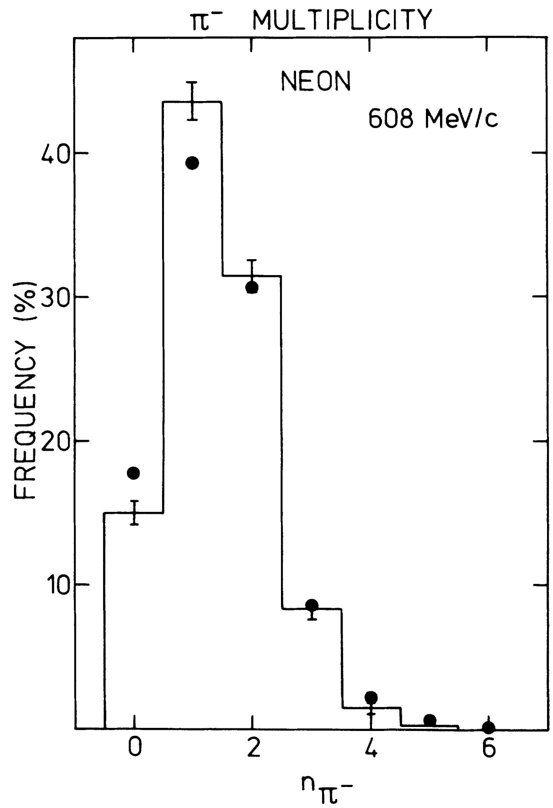

FIG. 5. Multiplicity distribution of negative pions from $\bar{p}$ annihilation on neon. Histogram; data from Ref. 15. Points; model predictions. The experimental mean value (Ref. 15) is 1.37 ± 0.04 to compare to 1.40 in the model.

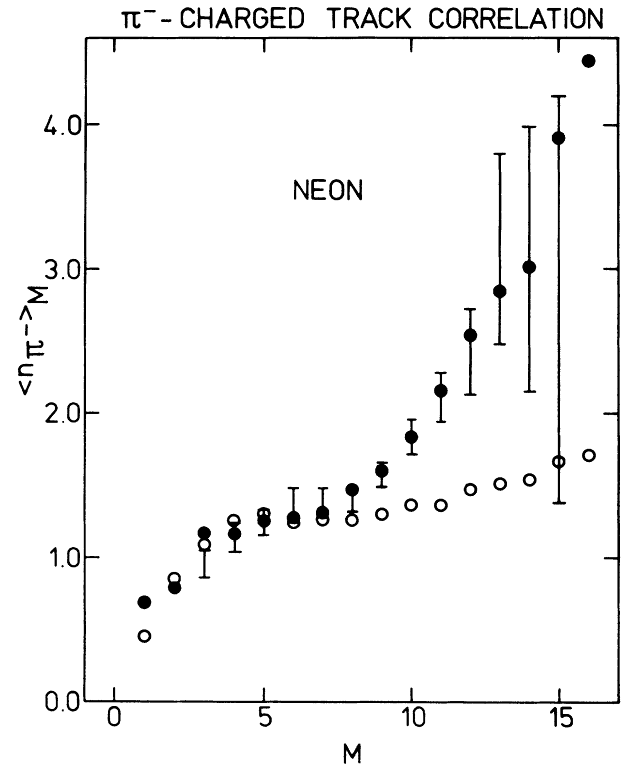

FIG. 6. Correlation between the mean number of negative pions and the number of charged tracks. The bars are data from Ref. 15. The solid circles are the predictions of the model. The open circles correspond to the relaxation of the condition of charge conservation (see text).

B. Correlation between negative pions and charge tracks

We have also studied the distribution of the mean number of negative pions per event $\langle n_{\pi^-} \rangle$ vs M, which has been obtained in neon. This distribution has a striking behavior. The number of π^-'s increases quite dramatically when M reaches high values (see Fig. 6). We reproduce beautifully this behavior (solid circles). Our result is a direct consequence of charge conservation. To emphasize this feature, we have run our model in picking at random the charge of each pion and assuming that the value of P_p and P_n stay *constant*, equal to their initial value, throughout the emission process; the result is shown in Fig. 6 by open circles. The difference between the two cases clearly shows that the correlation observed for $M \gtrsim 10$ is a result of the constraint of charge conservation and the quantitative agreement that we obtain shows that it has no dynamical content.

V. CONCLUSION

We have built a simple model for charged particle production, which accounts very well for existing multiplicity distributions in antiproton-nucleus annihilation. In particular, it explains very simply the strong correlation between the negative pion multiplicity and the total number of tracks; this is, to our knowledge, the first time that a quantitative prediction is made for that feature. The model embodies a clan production mechanism, where the clans are initiated by the interacting pions. We have also shown that it is consistent with the intranuclear cascade model, revealing at the same time that the latter generates clans, a feature which is not easy to point out in view of the fact that INC is a rather complicated, untransparent model. We want also to stress that our model presents a usefulness, which goes beyond the sample of experimental data studied here. It may be used to study correlation between different kinds of particles, including neutral particles and strange particles after a slight generalization.

In the present model, the clan structure is defined in terms of interacting hadrons. The number of clans is Poissonian and the nucleon number within a clan is also Poissonian. The charged track distribution results from a complicated superposition of charged pions (interacting and noninteracting) and protons. The picture is at variance with a previous analysis[9] in terms of NB. In the latter the number of clans is Poissonian and their size has a logarithmic distribution. Of course the average number of clans and their average size are not the same in both analyses. The present analysis indicates that in emulsion, (for 300 MeV/c), there are ~ 4.1 clans on the average against 5.64 for the NB fit; the mean number of charged tracks over the clans is 1.85, to compare with 1.32 in NB. For the neon case at 608 MeV/c, we observe 4.2 clans of 1.57 charged tracks, against 6.36 clans of 1.03 tracks in the NB fit. The presence within this fit of a number of clans larger than the number (~ 5) of primordial pions is somewhat embarrassing. Our present analysis is much more meaningful from the physical point of view. We believe this is due to the fact that we respect the constraints due to charge and baryon number conservation. The NB are more suited to situations where there is a large reservoir for the particle production, as it seems to be the case in high energy particle physics.[10,16]

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