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Negative Binomial Analysis of Charged-Particle Multiplicity in Antiproton-Nucleus Annihilation.

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Abstract. – The charged-prong multiplicity distributions measured in ($\bar{p}$-Ag/Br) annihilations (at rest and in the $p_{lab} = (300 \div 1400)$ MeV/c range) are fitted by negative binomials. The implications of the fits are discussed in the frame of a clan picture: pions from the annihilation are the originators (ancestors) of streaks which develop independently and lead to the ejection of particles (clan members). The average number of particles inside a clan appears independent of the $\bar{p}$-momentum and of the number of clans. This is related to a common, essentially exponential, decrease of the high multiplicities. The results are briefly compared to an intranuclear cascade calculation.

The study of charged-particle multiplicity distributions in inelastic collisions at high energy (from a few tens to a few hundreds GeV c.m. energy) and for various systems (pp, $\bar{p}$p, πp, e^+e^-, ...) has revealed that these distributions follow a negative binomial (NB) distribution, both for total multiplicities and for restricted intervals of pseudorapidity [1-3]. It is not clear yet whether this universal property is a signature of a peculiar aspect of the underlying dynamics or not. However, some arguments and observational facts strongly support the idea that the existence of NB distribution is linked to an underlying cascade processes in which «primary» objects (the ancestors in the language of ref. [4]) are created independently and subsequently generate the final particles (see fig. 1*a*)). In other words, each of the observed particles belongs to one of N clans; each clan is initiated by an ancestor and contains n_c particles. A NB distribution is obtained if N is a Poisson variable (independent clans) and if n_c follows a logarithmic law.

The parameters $\bar{n}$ and k entering the usual form of the NB law [5]

$$P(n) = \frac{k(k+1)\dots(k+n-1)}{n!}\left(\frac{\bar{n}}{\bar{n}+k}\right)^n \left(\frac{k}{\bar{n}+k}\right)^k \tag{1}$$

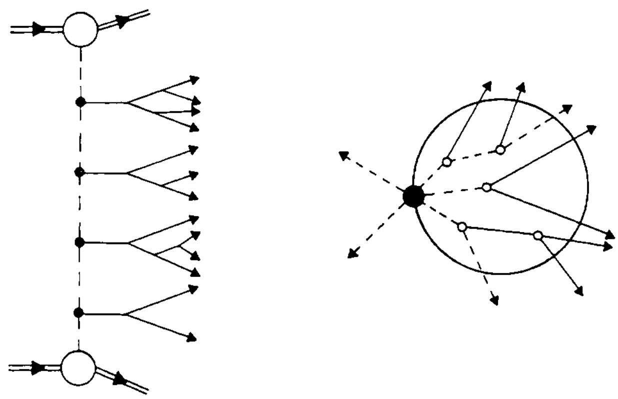

Fig. 1. – *a*) Schematic illustration of a clan production in a high-energy p-p collision. The ancestors indicated by dots are the partons produced in a hard interaction. *b*) Clan production in p̄-annihilation on a nucleus. The pions (dotted lines) originating from the annihilation site (heavy dot) propagate inside the nucleus and produce ejectiles which are members of the clans.

are then simply related to $\overline{N}$ and $\bar{n}_c$ by

$$\bar{n} = \overline{N}\,\bar{n}_c\,, \tag{2}$$

$$\overline{N} = k \ln\left(1 + \frac{\bar{n}}{k}\right). \tag{3}$$

In ref. [6], the possible existence of similar properties at lower energy in nuclear processes has been analysed by one of the authors; specifically, the ability of the intranuclear cascade (INC) dynamics, which is known to be relevant to the description of many nuclear processes, to develop NB distributions has been examined. It has been shown in particular that a necessary condition is the absence of strong constraints coming essentially from conservation laws, but also perhaps from dynamics. The p-nucleus and p̄-nucleus were indicated as the most favourable systems for the emergence of NB distributions, but the analysis may be considerably obscured by the mixing of different impact parameters, especially in the p-nucleus case. It was, therefore, concluded that special attention should be given to p̄-annihilation at rest on nuclei.

In the meantime, measurements of charged-prong multiplicity distributions for p̄-annihilation in emulsion have been published [7]. A photographic emulsion is a complex target, but the authors of ref. [7] claim that the largest part of annihilations ($> 80\%$) occur on either a Ag or a Br nucleus, which have similar mass. So, in a first approximation, we can consider that we deal with data for mass number $A \approx 100$.

The least-squares fits we obtained are shown in fig. 2 for annihilation at rest and at 300 MeV/c. Table I summarizes the fits for all the measurements. The NB distribution clearly gives a good description of the data. In the spirit of ref. [4], we now give an analysis of these fits in terms of clan production. In the light of model calculations [8], we expect that, more or less, each of the pions penetrating the nucleus induces a clan. Figure 1*b*) illustrates this idea. The fitted values of the NB parameters (see table I) correspond to an average number $\overline{N} \approx 3.5$ clans, which contain on the average $\bar{n}_c \approx 1.3$ charged particles. This seems quite reasonable, since about 2.5 pions interact with the nucleus. The somewhat larger value of $\overline{N}$ may be due to the extra contribution of noninteracting charged pions and to some

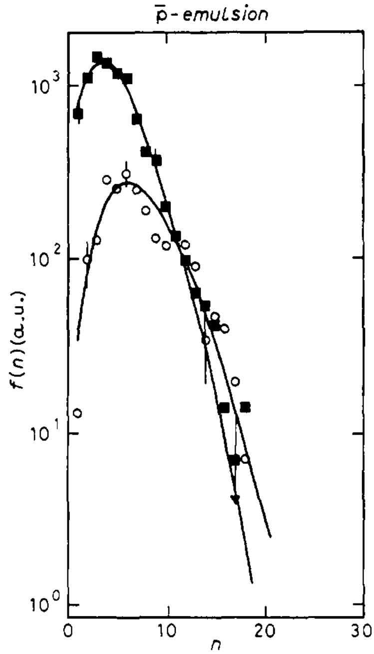

Fig. 2. – Best fit by negative binomials (full lines) of the charged-particle multiplicity distributions measured in p̄-annihilation in emulsion, both at rest (squares) and at 300 MeV/c (open dots). Typical experimental error bars are shown.

TABLE I. – *Parameters of the* NB *fits: Δ is the χ^2 per experimental point* (*eq.* (7.37), *p.* 151 *of ref.* [9]). *The other quantities are explained in the text.*

Energy (MeV/c)	Δ	$\bar{n}_{\text{exp}}$	$\bar{n}$	k	$\overline{N}$	$\bar{n}_c$	n_0
at rest	5.9	4.87	4.66	6.54	3.52	1.32	2.40
300	8.1	7.4	7.48	10.48	5.64	1.32	1.76
400	10.4	7.48	7.65	13.38	6.05	1.26	2.21
500	14.8	7.68	8.07	25.06	7.00	1.15	2.43
1400	7.3	8.5	8.99	12.81	6.81	1.32	1.71

breakdown of the independent growth of the clans (resulting from correlations, communication between clans, ...).

One may wonder about the mixed content (pions and nucleons) of the clans and whether this mixing is consistent with the interpretation of the NB recalled above. Along this line, one may speculate on the fact that, if pions are discarded from the analysis, the nucleons hit by the pions in the first place are to be regarded as the ancestors. Unfortunately, the measurements of the charged-baryon multiplicity are not available, but they would certainly be interesting.

A comparison with INC calculations is instructive. We have calculated the p̄-annihilation at rest on ^{98}Mo nuclei with our INC model, recently improved [8]. We got an average number of charged particles (pions and protons, in our case) $\bar{n} \approx 4.45$, which is reasonably close to the observed value. Moreover, we analysed the ejectile distribution (an ejectile being a nucleon kicked off the nucleus) and found that about 3.13 clans containing 1.45

ejectiles (both charges) are predicted. The figure is remarkably close to the fit mentioned above. Thus, the picture of clan formation seems to emerge both from model calculation and from experiment.

We turn to annihilation in flight. As mentioned already, the analysis may be less reliable because the contributions from the different impact parameters mix. However, the situation may be more favourable in the $\bar{p}$-nucleus system (compared, *e.g.*, to p-nucleus) for the relevant quantity seems to be the number of interacting pions, which is not very much dependent on the impact parameter. The fits by a NB are also very good for in-flight annihilation (although not as good as at rest) as shown in table I. The variation of the multiplicity distribution is consistent with the clan picture. Indeed, the average number of clans increases as expected: this number should follow the number of interacting pions, which increases because the annihilation site goes deeper inside the nucleus when the $\bar{p}$ momentum increases. On the other hand, the size of the clans is not changing very much; this is easily understood, since the energy of the pions increases very slowly in the studied energy range and, therefore, the properties of the clans they generate do not change much.

In ref. [7], it is stressed that the multiplicity distributions for all the antiproton momenta show the same exponential tail for $n \geqslant 10$. Again, this may be easily understood in our clan picture. Equation (1) yields

$$\frac{P(n+1)}{P(n)} = \frac{\bar{n}}{\bar{n}+k}\,\frac{n+k}{n+1}; \tag{4}$$

for $n \gg k$, this ratio is essentially a constant and, therefore, the tail of the NB is exponentially decreasing. In the cases analysed above, k is not negligible compared to n, but in the limited range $10 \leqslant n \leqslant 18$, we can write, to a good accuracy,

$$\frac{P(n+1)}{P(n)} = \frac{\bar{n}}{\bar{n}+k}\left(1+\frac{k}{n_{\mathrm{av}}}\right) \tag{5}$$

with $n_{\mathrm{av}} \approx 14$. In the same range, $P(n) \approx \exp[-n/n_0]$, which together, with (4), gives

$$\frac{1}{n_0} \approx \ln \frac{1+\dfrac{k}{\bar{n}}}{1+\dfrac{k-1}{n_{\mathrm{av}}+1}}. \tag{6}$$

The analysis of table I shows that the denominator is not changing very much from one case to the other; in fact, eq. (6) yields n_0 between 1.7 and 2.4, very close to the experimental value (~ 2.4). Therefore, n_0 is a constant because $k/\bar{n}$ is about the same for all cases. We notice from eqs. (2) and (3) that $\bar{n}_c$ is a function of $k/\bar{n}$ only. We conclude that the universal tail results from the constant size of the clans at the different momenta. This provides an alternative to the explanation put forward in ref. [7], in which the authors suggest that the universal tail is typical of deep-annihilation events. We note that the INC calculations of ref. [10] do not really indicate that high-multiplicity events are correlated to deep annihilations.

In conclusion, we have shown that NB multiplicity distributions have been observed in $\bar{p}$-nucleus annihilations, as was predicted in ref. [6]. We have also shown that the distributions are grossly consistent with the clan picture of ref. [4], the ancestors likely being the interacting pions. The size of the clans does not change very much and is responsible for the universal shape of the distributions. The remaining problem is to relate the size of the clans to dynamics. We have seen, however, that it is roughly explained by the INC model.

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