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ANTIPROTON-NEON ANNIHILATION AT REST AND AT 607 MeV/c

F. Balestra, S. Bossolasco, M.P. Bussa, L. Busso, L. Ferrero,
D. Panzieri, G. Piragino and F. Tosello
Istituto di Fisica Generale 'A. Avogadro', University of Turin and
INFN, Sezione di Torino, Turin, Italy

R. Barbieri, G. Bendiscioli, A. Rotondi, P. Salvini and A. Zenoni
Dipartimento di Fisica Nucleare e Teorica, University of Pavia and
INFN, Sezione di Pavia, Italy

Yu. A. Batusov, I.V. Falomkin, G.B. Pontecorvo,
M.G. Sapozhnikov and V.I. Tretyak
Joint Institute for Nuclear Research, Dubna, USSR

C. Guaraldo and A. Maggiora
Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy

E. Lodi Rizzini
Dipartimento di Automazione Industriale, University of Brescia and
INFN, Sezione di Pavia, Italy

A. Haatuft, A. Halsteinslid, K. Myklebost and J.M. Olsen
Physics Department, University of Bergen, Norway

F.O. Breivik, T. Jacobsen and S.O. Sorensen,
Physics Department, University of Oslo, Norway

ABSTRACT

The analysis is based upon $\bar{p}$ Ne annihilation events at rest and at 607 MeV/c detected with a self shunted streamer chamber exposed to the LEAR beams. The main measured quantities are the following: charged prong multiplicity, negative pion multiplicity; momentum, angular and rapidity distributions. General distributions are given as well as distributions as functions of charged prong multiplicity. A correlation is found between high multiplicity and depth of the annihilation point. The data are compared with recent theoretical analyses.

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1. Introduction

During the last years a number of theoretical speculations have been devoted to the study of the annihilation of low energy antiprotons on atomic nuclei. Some of them, founded on intranuclear cascade (INC) models, aim at predicting the observable features of this complicated process based on the more or less known elementary processes involved ($\bar{p}$ -nucleon interaction, π -nucleon interaction, nuclear evaporation and so on)[1-8]. The hope has been to discover some unusual phenomena by comparing the predictions of this conventional approach with experimental data.

Others have investigated theoretically the features of phenomena which cannot happen in the annihilation on free nucleons, such as the annihilation on two or more nucleons and the formation of a quark-gluon plasma [9-25]. These phenomena are expected to be highly favoured if the annihilation occurs deeply inside the nucleus and, according to Rafelski [9-11], should be characterized by an abnormal production of strange particles and of very energetic protons. The features of strangeness production should also probe the quark structure of hadrons and nuclei.

Conclusions very similar to those obtained by Rafelski have been reached also by a different approach [14] based on kinematical constraints in a pure hadronic phase.

In the mean time, a lot of experimental data have emerged and this paper contributes to this field with an investigation on the annihilation of $\bar{p}$ at rest and at 607 MeV/c (179 MeV) on Ne nuclei. The data have been obtained with a self-shunted streamer chamber in a magnetic field exposed to the $\bar{p}$ beams of LEAR at CERN. This investi-

gation extends our previous analyses based on the charged prong multiplicity between 200 and 600 MeV/c [26] and on the strangeness production [27]. In this work we give the multiplicities and the angular and energy features of the negative pions and of the nuclear fragments at rest and at 607 MeV/c; these quantities are given generally and as functions of the charged prong multiplicity. The problem of the identification of the deep annihilations is re-examined and the evidence for a correlation between annihilation depth and high multiplicity, pointed out previously [26], is strengthened. The data are compared with INC model predictions and with other experiments.

As the INC calculations reproduce satisfactorily the gross features of the annihilation events, we examine a great number of distributions in order to detect any unpredicted feature or to refine the theoretical models.

The paper is organized as follows. In Sect. 2 the experimental apparatus is briefly described. In Sect. 3 our ability in reconstructing the events, measuring angles and momenta and identifying the annihilation products, is discussed shortly. In Sect. 4 the overall angular and energy features of the events at rest (Sect. 4.2) and at 607 MeV/c (Sect. 4.3) are given. Sect. 5 is dedicated to the charged prong multiplicities (5.1 and 5.2) and to the dependence of angles and momenta on the multiplicities (5.3.1 Kinetic energy, 5.3.2 Isotropy, 5.3.3 Rapidity). In Sect. 6 the method of identifying deep annihilations is treated. In Sect. 7 some results of the INC model calculations are compared with our data. In Sect. 8 we summarize our results and draw conclusions.

2. Experimental apparatus

The experimental apparatus consisted of a self-shunted streamer chamber in a magnetic field and was exposed to the $\bar{p}$ beams of the LEAR facility at CERN. The details of the apparatus and its performances are reported in ref. [28]. The chamber, having a sensitive volume of $70 \times 90 \times 18 \text{ cm}^3$, was filled with natural neon (90.92% of ^{20}Ne , 0.26% of ^{21}Ne and 8.82% of ^{22}Ne) at about 970 mbar and 25°C . Temperature and pressure were measured during each data-taking session and their relative variations did not exceed a few parts per thousand. The effective beam energy for the antiprotons in flight was estimated to be 179.6 MeV (607.7 MeV/c). The magnetic field was 0.805 T.

Annihilations of $\bar{p}$ at rest were also detected with a magnetic field of 0.4 T. The beam was degraded down from an initial momentum of 200 MeV/c to make the $\bar{p}$ stop in the central region of the gas target.

3. Event reconstruction

We have measured 3397 annihilation events at rest and 4645 at 607 MeV/c following standard procedures. The events were reconstructed by means of the Hydra geometry program. Some features of our pictures and of the events and the performances of our apparatus in the detection of events and in their reconstruction are like those described in Ref. [26,29] for annihilation in ^4He and Ne. In the analysis of events on Ne, however, electric charge conservation and ionization are not useful in the mass identification such as in ^4He . The reliability of our reconstruction procedure is supported by the isotropy displayed by the events measured at rest.

For each event we recorded the number of charged prongs and, for

each prong, measured the momentum based on curvature or range. Concerning the charged prong multiplicity, we underline the ability of our apparatus to detect very slow particles. We notice that the shortest tracks we can measure are few millimeters in length. For instance would a 6 mm long track in Ne correspond, to a proton of 0.2 MeV.

The prongs were divided into negative and positive tracks by the curvature sign. The separation efficiency decreases as the track direction approaches the magnetic field direction (vertical direction) due to both shorter tracks and lower effective field. Comparing the numbers of tracks emitted left and right and those emitted up and down with respect to the beam direction, we deduced a systematic error in the negative track identification below 5%. A part from π^- , the negative tracks in the annihilations at rest include K^- (in $\sim 2\%$ of the events). We cannot distinguish these two particles and in the following we shall neglect the presence of K^- .

In the events in flight, the negative tracks also include $\bar{p}$ due to inelastic scattering and break-up reaction (elastic events can be recognized by means of a kinematical fit). These reactions affect only events with one negative track and, presumably, with a low charged prong multiplicity. Inelastic scattering and break-up are expected to be less than 5% of all non elastic events [26].

The positive prongs include π^+ , K^+ ($\sim 2\%$ of the events), protons and heavier nuclear fragments. In the case of stopping tracks with detected curvature it was possible to identify the most probable mass by a χ^2 test. Their kinetic energy is less than 12 MeV in 99% of the tracks. It was not possible to identify the other positive tracks, but stopping tracks with undetectable curvature are certainly due to nuclear fragments. For non stopping tracks we know the momentum

due to nuclear fragments. For non stopping tracks we know the momentum and the direction, but not the energy or the velocity.

In spite of the impossibility of identifying most of the positive tracks, it is possible to extract some information concerning the nuclear fragments, which, although rough, is interesting in connection with the features of the π^- distributions. We assumed that the momentum distribution of the π^+ is equal to that of π^- [30] and that the ratio between the number of π^+ and that of π^- is 0.8 (see Sect. 5.1). Then we subtracted from the momentum distribution of all the positive particles that of the π^- multiplied by 0.8. The residual momentum distribution should concern nuclear fragments only.

To obtain kinetic energy and rapidity distributions we assigne to the stopping particles the most probable mass and to the others the π mass. Applying the same procedure as for momentum we got the kinetic energy and rapidity distributions of the fragments. We stress that in the following we will not consider the absolute values of energy or rapidity of the nuclear fragments, but the variation of the distributions as functions of the charged prong multiplicity.

4. Overall angular and energy features of the annihilation events.

4.1 Introduction

To understand qualitatively the features of the data, it is convenient to bear in mind some features of the annihilation events on free nucleons at rest and at 607 MeV/c. In the annihilation at rest, laboratory and center of mass systems coincide. The pions are emitted isotropically with an energy spectrum ranging from 0 up to 1 GeV with a maximum around about 170 MeV (276 MeV/c) [see Fig. 2a, dotted line]. This value is close to the resonance energy of the π -nucleon interac-

tion.

In the $\bar{p}$ -nucleon annihilations in flight, the $\bar{p}$ -nucleon center of mass moves in the laboratory system with velocity $\beta = 0.3$. The angular distribution of the π^- will be peaked forward and the pions emitted forwards will be more energetic than those emitted backwards (at $\theta = 0^\circ$ the peak energy is calculated to be ~ 242 MeV (355 MeV/c) and, at 180° , ~ 88 MeV (180 MeV/c)). The degree of anisotropy can be seen in the distribution of the $\cos\theta$ (Fig. 4), and in the rapidity distribution (Fig. 5). θ is here the angle between the incoming $\bar{p}$ and the π^- , and the rapidity of a particle is defined as [31]

$$y = \frac{1}{2} \ln \frac{1+\beta_L}{1-\beta_L}$$

where β_L is the longitudinal component of the velocity.

The value β of β_L corresponding to the mean value of y over a number of particles is the velocity of the reference frame in which the emitted particles have the mean value of the rapidity equal to zero. Of course, if the particles are emitted isotropically, $\langle y \rangle = 0$.

Assuming that this reference frame is associated to the center of mass of the system made up by the antiproton and a nuclear mass M , on which it annihilates, expressed in terms of the nucleon mass ($M=Nm$), one has

$$\beta = \frac{p_{\bar{p}}}{W_{\bar{p}} + Nm}$$

where $p_{\bar{p}}$ is the $\bar{p}$ momentum and $W_{\bar{p}}$ the total energy. Since the rapidity increases with β , y increases with $p_{\bar{p}}$ and decreases with N . For $p_{\bar{p}}=607$ MeV/c and $N=1$, $\beta=0.295$ and $y=0.304$. For $\beta \lesssim 0.3$, $y \simeq \beta$. The behaviour of $y \simeq \beta$ vs. N , for different values of $p_{\bar{p}}$, is shown in Fig.

1.

4.2 Annihilation at rest

Now let us consider the $\bar{p}$ Ne data, beginning with the events at rest. Fig. 2a shows the π^- momentum distribution compared to the corresponding distribution of the reaction $\bar{p}+n \rightarrow \pi^- + \text{anything}$ in deuterium [30]. The spectrum in Ne is less energetic, as a consequence of the energy transfer from the pions to the nucleus. In particular, the peak of the distribution is around 130 MeV/c instead of around 275 MeV/c. Fig. 2b shows the corresponding momentum distribution of the nuclear fragments (proton, deuterons and so on). The distribution of the longitudinal momentum of the π^- with respect to a direction perpendicular to the chamber front wall, shown in Fig. 3a, displays a forward-backward symmetry. The same feature appears also in the rapidity distribution (Fig. 3b).

The annihilation at rest in nuclei is expected to be essentially a peripheral phenomenon (see Sects. 6 and 7.1), so some pions will interact with the residual nucleus and some others will not. Hence, the pion angular distribution is not expected to be isotropic in a reference system in which the polar axis is directed along the momentum of the recoil nucleus [1], but isotropy will be found if the polar axis is chosen arbitrarily, as we have made in the above distributions.

4.3 Annihilation in flight (607 MeV/c)

The features of the annihilation events at 607 MeV/c are displayed by the π^- distributions of $\cos \theta$ (Fig. 4), rapidity (Fig. 5), momentum (Figs. 6 and 7), π^- longitudinal momentum (Fig. 8a), π^- transverse momentum (Fig. 8b) and kinetic energy (all π^- , forward and

backward π^-) Figs. 9a,b.

The distributions observed in Ne are like those described previously for annihilation on free nucleons but the degree of anisotropy is smaller. The $\cos\theta$ distribution is less peaked forward and the mean value of the rapidity is lower (about 0.25 instead of 0.3 for the free nucleon case) (Figs. 4 and 5). A similar result is reported in Ref. 33 for the π^+ inclusive distribution from $\bar{p}$ annihilation on ^{12}C and ^{238}U at the same energy as ours.

The π^- from Ne are, on average, less energetic than those produced on free nucleons (Fig. 6), due to collisions with nucleons in the nucleus. Moreover the forward ejected π^- are more numerous and more energetic than those emitted backwards (Fig. 9b). Note that there is a peak around 70 MeV both in the forward and the backward directions, but more pronounced backwards. Forwards there is an excess of more energetic pions, with a large bump around 350 MeV.

Very roughly, the pions which have interacted strongly with the nucleus contribute to the lower energy peak both backward and forward. The backward peak is more prominent because it also contains backward going (in the $\bar{N}N$ center-of-mass frame) "primordial" pions (those coming from peripheral annihilations and not interacting with the nucleus). These backward emitted pions appear at low energy due to the motion of the $\bar{p}$ -nucleon center of mass. Primordial pions ejected forward contribute to the forward high energy bump.

Recently, the two bump structure in the momentum spectrum has been seen also for the π^+ produced in the annihilation of 608 MeV/c $\bar{p}$ on ^{12}C and ^{238}U [33] and on ^{28}Si [34]. The high energy bump appears in the same momentum region as for Ne, while the low energy peak appears

at higher values than for Ne. The difference might be due to the low momentum cut off (about 100 MeV/c) determined by the detector acceptance of Ref. 33.

5. Charged prong multiplicity and related quantities

5.1 Charged prong and π^- multiplicities

In a $\bar{p}$ -nucleon annihilation process at our energies 5 pions are produced on average ($2\pi^-$, $1\pi^+$ and $2\pi^0$ on n; $1.5\pi^-$, $1.5\pi^+$ and $2\pi^0$ on p). In ^4He , ^2H and ^{12}C at most $4\pi^-$ have been observed [35,36,37] and the ratio between the number of π^+ and that of π^- is about 0.8 (see Tab. 1). From this number one can deduce a maximum number of charged pions in Ne of 7.2. The Ne charge is 10, so from the disintegration of the Ne nucleus we can obtain at most 9.5 heavy charged prongs. Therefore, we can get at most about 16.7 charged prongs in an annihilation event on Ne.

Fig. 10a and 11a show the multiplicity distributions at rest and in flight. One sees that the charged prong multiplicity M reaches the maximum value of 14 at rest and of 16 at 607 MeV/c.

In Figs. 10b and 11b the mean numbers of π^- per event, $\langle n_{\pi^-} \rangle$, are given as a function of M . $\langle n_{\pi^-} \rangle$ increases with M both at rest and in flight. Assuming a mean number of π^+ equal to $0.8\langle n_{\pi^-} \rangle$ for each M , we can obtain the mean number of nuclear fragments per event as

$$\langle n_f \rangle = M - 1.8 \langle n_{\pi^-} \rangle$$

$\langle n_f \rangle$ as function of M is given in Figs. 10d and 11d. One sees that the mean number of fragments increases up to ~ 7 at rest and up to ~ 8 in flight. In these extreme cases the Ne nuclei are completely destroyed.

We note that the fraction of events with high $\langle n_f \rangle$ is much higher in flight than at rest, as it is shown in Tab. 2, where the fractions

of events with $\langle n_f \rangle$ higher than some typical values are given. In Tab. 2 the values of $\langle n_{\pi^-} \rangle$ corresponding to the chosen values of $\langle n_f \rangle$ are also given. One sees that a given $\langle n_f \rangle$ is accompanied by a lower number of π^- in flight than at rest (see also Fig. 12).

Figs. 10c and 11c give the different contributions (in percentage) to the π^- production for each value of M in events with 0, 1, 2, etc. π^- . As M increases, the contribution from the events with 0 and 1 π^- decreases; the contribution from events with 2 π^- firstly increases and then decreases; the contribution from the events with more than 2 pions increases monotonically.

Clearly, Figs. 10 and 11 show a correlation both at rest and in flight between high multiplicity and high number of emitted π^- (or π^+), but there is a strong difference in the percentages of high multiplicity events at rest and in flight. This can be ascribed to the occurrence of annihilations inside the nucleus, as will be discussed in Sect. 6.

In Fig. 13 the π^- multiplicities in Ne are compared with those obtained in ^2H at 170.5 MeV [36], in ^4He at 179.6 MeV/c [37], in ^{12}C below 200 MeV [35] and in photographic emulsion below 250 MeV [38] (the π^- multiplicities at rest in ^4He and ^2H do not differ essentially from those in flight). Since in Refs. 35 and 38 the joint distributions of π^- and π^+ are given, we have deduced the approximate π^- distributions assuming that pion-nucleon charge exchange [43,44] and pion absorption effects do not seriously affect the ratio between the numbers of π^+ and π^- . In fact, under these assumptions the numbers of $\pi^\pm$, of π^+ and of π^- , correspond as follows:

n_{π^+}	n_{π^-}	n_{π^0}
0	0	0
1	0	1
2	1	1
3	1	2
4	2	2
...		

which allows to find easily the π^- multiplicity distribution. Going from ^2H to Ag/Br, we see a systematic decrease of the fraction of the events with higher π^- multiplicity and an increase of those with lower π^- multiplicity. A similar change is found by comparing the data on Ne at rest and in flight. This behaviour is an indication of the stronger interaction between the annihilation pions and the nucleons as the mass number increase and hence the interaction energy as well.

The π^- production in different nuclei is also given in Tabs. 1 and 3. $\langle n_{\pi^-} \rangle$ decreases as a function of A. If we define the absorption with respect to the production on ^2H ($(\langle n_{\pi^-} \rangle_{^2\text{H}} - \langle n_{\pi^-} \rangle_A) / \langle n_{\pi^-} \rangle_{^2\text{H}}$), we find that it increases from ^4He to emulsion (last line in Tab.1). The ratio $\langle n_{\pi^+} \rangle / \langle n_{\pi^-} \rangle$ is almost constant for the nuclei where the number of protons is equal to the number of neutrons.

5.2 Stopping tracks

The mean number per event of stopping tracks at rest increases up to $M=7$ and then remains constant, while in flight it reaches a maximum for M between 7 and 10 and then decreases [Fig. 14]. The stopping tracks have a kinetic energy ≤ 12 MeV. The number of detected stopping tracks depends on the volume and the density of the target, on their orientation and on the value of the magnetic field (with a higher

value of the field more tracks will stop within the target volume). Therefore this number has a limited meaning. Nevertheless, it reveals an interesting difference between the data at rest and in flight. In fact, we see that in flight, where a higher value of the magnetic field was used, $\langle n_s \rangle$ is lower than at rest. This indicates that in the annihilations in flight a higher energy is transferred to the nuclear fragments than is the case at rest.

5.3 Kinematical quantities as functions of M.

In this Section we show the dependence of various kinematical quantities of the annihilation events as functions of the charged prong multiplicity M both at rest and at 607 MeV/c.

We will consider the following mean quantities: $\langle T_i \rangle$ (kinetic energy), $\langle T_{Fi} \rangle$ and $\langle T_{Bi} \rangle$ (kinetic energy of forward and backward emitted particles), $\langle p_i \rangle$ (momentum), $\langle p_{Li} \rangle$ (longitudinal momentum), $\langle y_i \rangle$ (rapidity) and $\langle F/B \rangle_i$ (ratio between the number of particles emitted forwards and particles emitted backwards). Both negative pions ($i=\pi^-$) and nuclear fragments ($i=f$) are considered. Moreover, note that $\langle \cos\theta \rangle$ is only given for π^- , while $\langle F/B \rangle$ concerns all prongs (negative plus positive).

5.3.1 Kinetic energy and momentum

The mean kinetic energy and the mean momentum of the π^- decrease slightly at rest and strongly in flight as functions of M (Figs. 15a,b and 16a,b). Moreover, for each M , the π^- emitted forward in flight are more energetic than those emitted backwards (Fig. 17).

The mean momentum of the fragments increases similarly as a function of M both at rest and in flight (Figs. 16 c,d).

The total energy per in flight event (kinetic plus mass energy) carried by the π^- ($\langle W_{\pi^-} \rangle = \langle n_{\pi^-} \rangle (\langle T_{\pi^-} \rangle + m_{\pi^-})$) increases as a function of M from 400 MeV at M=3 up to 800 MeV at M=14. A similar behaviour is exhibited by the total energy at rest (Fig. 18).

5.3.2 Isotropy

As we have said previously, in the $\bar{p}$ -nucleon annihilation at rest the pions are emitted symmetrically forwards and backwards. This feature is maintained in the annihilations at rest on nuclei, as both the $\bar{p}$ -nucleon and the $\bar{p}$ -nucleus frames coincide with the centre of mass frames. In our data at rest, the forward-backward symmetry is displayed for each value of M and within the statistical fluctuations we get by $F/B \simeq 1$ and $(F/B)_{\pi^-} \simeq 1$ (Figs. 19 a,c).

On the contrary, the asymmetry is clearly displayed by the data in flight (for instance $F/B \neq 1$, $(F/B)_{\pi^-} \neq 1$, $\langle P_{L\pi^-} \rangle \neq 0$, $\langle \cos \theta \rangle \neq 0$; see Figs. 19 b,d, 20, 21), which show also that the anisotropy varies strongly with M, the events being highly anisotropic for low M and quite symmetric for high M.

5.3.3 Rapidity

In Fig. 22 a we show the average rapidity $\langle y_{\pi^-} \rangle$ as a function of M. There is a strong correlation between the rapidity and M. The value of $\langle y_{\pi^-} \rangle$ is about that expected from annihilation on free nucleons (0.3) for M=4-5 and decreases down to about 0.1 for higher values of M. (The high value for M=3 shown in Fig. 22a might be due to a contamination of $\bar{p}$ in the final state, as $\bar{p}$ is not distinguishable from π^- [26]).

Summing up we see that the pions from events with lower M have higher values of momentum, anisotropy and rapidity, and the values are close to those for pions produced in the annihilation on free nucleons. The same quantities are quite different for higher M , revealing that other phenomena occurred, besides the quasi free $\bar{p}$ -nucleon annihilation.

Let us consider the following possibilities:

(a) Before being annihilated, the initial antiproton may undergo elastic and inelastic scattering on a number of nucleons. When the annihilation occurs, the $\bar{p}$ momentum is lower than 607 MeV/c and the produced pions will have a rapidity lower than 0.3 (See Sect. 4.1).

(b) After the annihilation, the pions may interact elastically and inelastically with the residual nucleus and may be absorbed (See Sect. 7), thereby losing energy and spreading out in angle. This reduces the longitudinal momenta and, consequently, the average rapidity.

(c) Independently of the previous phenomena, the pure annihilation process might also involve two or more nucleons (See Sect. 1). This should imply a value of the average rapidity smaller than 0.3; for instance, if we have 2 nucleons, $y=0.2$.

Thus, in the $\bar{p}$ nucleus annihilation, an involvement of many nucleons would lower the mean rapidity through various mechanisms. This is just in agreement with the behaviour of the number of nuclear fragments and their energy as a function of M illustrated in the previous sections.

Fig. 22b shows $\langle y_{\pi^-} \rangle$ as a function of p_T . For $p_T > 200$ MeV/c, the mean rapidity is about 0.3, i.e. consistent with the assumption of

primordial pions only. For $p_T < 100$ MeV/c, it is about 0.15; this low value indicates that there was a strong involvement of nucleons.

The situations of low and high rapidity are described in more detail in Figs. 22c,d. The first one gives the rapidity distribution for $p_T < 100$ MeV/c, the latter one for $p_T > 400$ MeV/c. The experimental histograms are compared with those obtained for free $\bar{N}N$ annihilation. For $p_T < 100$ MeV/c, the two histograms are different, as expected. But some differences appear also for $p_T > 400$ MeV/c. A similar situation exists also in the rapidity distributions of π^+ from annihilations on ^{12}C and ^{238}U at our energy, reported in Ref. 33, where the data are compared with INC calculations. Although the mean multiplicity for high p_T is compatible with the interpretation that the high p_T pions are primordial, the behaviour of the multiplicity distributions is not well reproduced by the calculations.

In Fig. 23 the rapidities of the fragments at rest and in flight are displayed. As expected, the mean rapidity in flight is a bit higher than zero.

5.3.4 A general remark

Please note that $\langle n_{\pi^-} \rangle$, $\langle p_{\pi^-} \rangle$, $\langle F/B \rangle$, $(F/B)_{\pi^-}$, $\langle p_{L\pi^-} \rangle$ and $\langle y_{\pi^-} \rangle$ in flight have more or less wide plateaus between $M=6$ and $M=10$ (Figs. 11b, 16b, 19b,d, 20 and 22a). In this region $\langle n_s \rangle$ reaches its maximum value and the events with 1 and 2 π^- predominate strongly and with the same weight (see Fig. 11c).

6. Deep annihilations

In our previous work [26] concerning the interaction of $\bar{p}$ with Ne nuclei between 19.7 and 179.6 MeV, we have given evidence that a high

multiplicity of charged prongs may be considered as a signature of annihilations occurring deeply inside the nuclei.

Our conclusions were based mainly on the following arguments. We found events with $M < 16$ and, for convenience, we defined high multiplicity as greater than 9, the atomic number of Ne being 10. For $M \geq 10$, the mean number per event of charged prongs is about 11, of which 3.5 are charged pions and 7.5 are nuclear fragments; hence many nucleons are involved in the interaction and the nuclei are completely destroyed. Moreover for $M \geq 10$, the reaction cross section is nearly independent of the energy. On the contrary, for $M < 10$, the total reaction cross section decreases as the $\bar{p}$ energy increases, as in the interaction of $\bar{p}$ on free nucleons. The mean number of charged prongs (5; 2 charged pions and 3 heavy particles) is close to that found in the $\bar{p}^4\text{He}$ interaction (~ 4) [37], i.e. fewer nucleons are involved.

Also in the light of intranuclear cascade models, we concluded that events with $M < 10$ have the characteristics of annihilations on the surface of the nucleus and those with $M \geq 10$ have the characteristics of annihilations occurred in the interior of the nucleus.

The same conclusions were drawn from the analysis of the multiplicity distributions between 0 and 1400 MeV of annihilation events in photographic emulsion [39].

The above statements are supported also by comparing the multiplicity distribution at rest with that at 179 MeV, which are displayed in Figs. 10a and 11a. The percentage of events with $M \geq 10$ at rest is only 7% against 15% at 179 MeV.

Let us reconsider the above arguments in the light of the measurement of momenta and angles described in the previous Sections.

If the annihilations in flight occur on nucleons bound on the surface of nuclei, one expects some of the pions to interact with the residual nucleus. Therefore, the angular distribution of the pions in the laboratory ($\bar{p}$ -nucleus) system will be less anisotropic than in the case of annihilations on free nucleons, the pions will be less energetic and the forward/backward ratio will be smaller.

If the annihilations occur deeply inside the nucleus, the emerging pions will be still more isotropic as most of them will interact with nucleons and forget their original features.

In short, interactions between pions and nucleons lead towards isotropy and deep annihilations imply a lot of such interactions. Correspondingly, we expect that these interactions increase the number and energy of nuclear fragments. Of course, the degree of symmetry is not a useful parameter in the annihilation at rest, where we have isotropy. But, also at rest, deep annihilations will produce more energetic nuclear fragments than annihilations on the surface do.

We notice that the correlation between annihilation depth and energy deposited by pions in a nucleus has been seen experimentally with a Si target [34]. So the deeper the annihilation, the higher the energy deposited.

We have shown previously that the degree of isotropy of the ejected pions increases with M . Now we analyze more in detail two samples of events at 607 MeV with low ($M=4$) and high ($M=11$) multiplicity, respectively.

The data are displayed in Figs. 24-26. We call the attention to the events in flight and note that: (a) the mean kinetic energy for $M=4$ is higher than that for $M=11$ (270 MeV against 190 MeV) (Fig. 25); the same holds for the momentum (Fig. 26); (b) for $M=4$ the mean

kinetic energy carried by the forward emitted pions is higher than that carried by those emitted backwards (320 MeV against 190 MeV), while for $M=11$ the two quantities are nearly the same (184 MeV against 187 MeV) (Fig. 25); (c) for $M=4$, the mean value of the rapidity is 0.37, while for $M = 11$, the mean rapidity is 0.11, (Fig. 26); (d) for $M = 4$, the distribution of $\cos\theta$ is peaked forwards, while for $M = 11$ it is nearly flat, thus indicating an isotropic distribution of the pions in the laboratory system (Fig. 26); (e) according to (d), the distribution of the longitudinal momentum extends mainly in the forward direction for $M = 4$ and is nearly symmetric around 0 for $M = 11$ (Fig. 26).

As a last remark, we note that annihilations produced by stopping $\bar{p}$ are mainly annihilations on the surface of the nucleus. As we have seen in Sect. 5.1, also in this case the nucleus can be broken up completely in connection with the production of a higher number of π^- , but complete break-up occurs with a lower probability than in flight: for example, $\langle n_f \rangle \geq 5.4$ in 13% of the cases at rest and in 40% in flight (see Tab. 3). Hence, we can conclude that the higher percentage in flight of stopping tracks is due to annihilations occurring deeper in the nuclear matter. We have also seen that in order to produce the same number of fragments a smaller number of π^- is needed in flight than at rest (see Fig. 12).

Although there must be an overlap between deep and peripheral events, it is reasonable to conclude again that the majority of the high multiplicity events in flight are deep annihilations.

7. Comparison with INC model calculations

In this section we compare our results with some predictions of the INC model calculations concerning both Ne and other nuclei at different $\bar{p}$ energies.

In INC models, at each annihilation event, on average 5 pions are generated according to the multiplicities and momenta known from data and models on $\bar{p}$ -N annihilation. The interaction of the pions with the residual nucleus is described in terms of a cascade of π N and NN interactions generated with Monte Carlo techniques. Basically, a pion may be scattered elastically, inelastically or with charge exchange ($\pi N \rightarrow \pi N$), may produce another pion on one nucleon ($\pi N \rightarrow \pi \pi N$), or may be absorbed by a pair of nucleons ($\pi NN \rightarrow NN$). The pions interacting with the nucleons via the Δ resonance ($\pi N \rightarrow \Delta$, $\Delta N \rightarrow NN\pi$, $\Delta N \rightarrow NN$) are those coming from annihilations with production of 4, 5 and 6 pions. A fraction of the pions are absorbed. There is uncertainty about the detailed mechanisms of energy transfer to the nucleons. Generally it is assumed that a number of nucleons are hit by the pions and ejected, leaving a bound nucleus which de-excites emitting low-energy nucleons or nuclear fragments ($T < 50$ MeV). In some calculations the low energy particles are neglected or not treated adequately. An evaporative cascade is considered in the calculations of Refs. [1,5,8,34].

The comparison with our experimental data, although qualitative, is not straightforward, because in some cases the quantities investigated in the experiment are not those displayed in the published theoretical papers. Moreover, in some calculations the low energy nucleons as well as the heavier nuclear fragments, are neglected. On the other hand, our experiment can give no information on the neutral particles emitted (with the exception of the strange particles). Nevertheless, some interesting points come out of the analysis.

However, very recently, unpublished analyses have dealt with some specific results of our experiment and will be presented below.

7.1 Annihilation at rest

The annihilation at rest is studied in Refs. 1,5,8. It is predicted to be essentially a peripheral phenomenon, so that the energy spectrum of the pions should not deviate substantially from that of annihilation on a nucleon [1]. A similar result is found also by Hernandez and Oset [52]. In spite of the surface character of the $\bar{p}$ absorption, the process may induce a heavy break-up of the nucleus [1,5]. Our momentum distribution (Fig. 2a) is shifted remarkably with respect to the free nucleon case, which seems to contradict the predictions mentioned. The presence of the high multiplicity tail in Fig. 10a together with Fig. 10d supports the prediction on strong break-up.

7.2 Annihilation in flight

(i) Some predictions on the annihilation events in flight common to all the INC model calculations, are [2,4,5,7,33,34]:

- 1) The π momentum distribution is characterized by a two bump structure;
- 2) The higher energy bump is more important in the forward direction;
- 3) In the backward hemisphere lower energy pions dominate;
- 4) The pions are more numerous in the forward hemisphere than backwards;
- 5) Nuclear fragment emission is quite isotropic;

6) A non negligible number of annihilations occur deeply inside the nuclei.

These overall features are displayed qualitatively by our data, as shown in the previous sections.

A quantitative comparison is performed in Figs. 27 and 28, where some experimental histograms are superimposed on histograms calculated specifically for Ne at 607 MeV/c by Oset [52] with the model described in Ref. 7. This model incorporates higher-order quasi elastic contributions as well as two- and three-body absorption. A consequence is that more pions are absorbed compared to the results from other intra-nuclear cascade calculations. One sees that the kinetic energy distributions agree well with the data above 150 MeV and disagree below, which is the energy region where the π^- have interacted strongly with the nucleons; the experimental distribution is shifted toward lower energies (Fig. 27). Discrepancies appear also in the $\cos$ distribution (Fig. 28): more (less) pions are found in the backward (forward) hemisphere in the experimental histogram than in the calculated one. Thus, the experimental distribution is less anisotropic than the theoretical one. It seems that some mechanisms favouring the production of low energy pions are not adequately considered in the theory.

(ii) Fig. 11b shows a direct correlation between the number of negative pions and that of the total charged prongs, which is reproduced in a satisfactory way by a recent version of the INC model [53]. This gives a much better description of the elementary NN interaction, includes the effect of the local reduction of the nuclear density during the development of the cascade and takes into account the de-excitation of the residual nuclei in terms of evaporation and multifragmentation.

The model reproduces also satisfactorily our charged prong distributions at 600 MeV/c and at 300 MeV/c [26].

(iii) The direct correlation shown in Fig. 11b has also been fitted fairly well recently within a schematic model utilizing a clan picture, where the ancestors are the pions [54]. The same model reproduces very well the charged prong and the negative pion multiplicities from Ne (reported in the present work) and from emulsions [39]. According to the authors, the success of their model depends strongly on the constraints due to charge and baryon number conservation, which are imposed at each step of their procedure. This explanation agrees with our simple analysis in Sect. 5.1. Note, also, that the model reproduces the plateau in the distribution of $\langle n_{\pi^-} \rangle$ as a function of M pointed out in Sect. 5.3.4. In the model, the assumption that Ne has an alpha-cluster structure plays also an important rôle.

(iv) In Ref. 26 and Sect. 6 of the present work a correlation is indicated between high multiplicity of charged prongs and depth of the annihilation point. Such a correlation has not been found in Ref. 5. Instead, a correlation has been shown to exist between charged prong multiplicity and number of interacting pions. But, also based on the comparison in sect. 6 between data at rest and in flight, it is evident that the higher the number of annihilation pions, the higher is the probability that pion-nucleon interactions occur; and, for a given pion multiplicity, the deeper the annihilation, the higher is the probability of pion-nucleon interaction. Both facts favour a high multiplicity.

(v) In Tab. 4 the absorption of π^- found in ^{20}Ne is compared to the absorption evaluated in some calculations. We make the comparison

using the nuclei closest to Ne among those studied. We see that, at rest, the value found by Iljinov et al. for ^{12}C (which agrees well with the experimental value, see Tab. 2) is close to the value for Ne; the values estimated for Mo in Refs. 5 and 8 seem to be too small. At 175 MeV, both the values calculated by Hernandez et al. and by Clover et al., for ^{12}C , are close to the value found for Ne. Finally, the value calculated by Cugnion et al. for Ca at 100 MeV seems to be too small. Note that the absorptions of π^- , $\pi^\pm$ and all pions seem to be almost equal.

8. Conclusions

The main aim of this work is to add experimental data to our knowledge of the complicated phenomenon of the annihilation in nuclei. These data can be compared to theoretical predictions based on standard physics, with a twofold purpose: to improve the models and, possibly, to discover something new. We have given a wide and detailed description of the momentum and angular distributions of the negative pions and of the nuclear fragments. Due to the 4π acceptance of our apparatus and the low density gas target, we were able to detect very carefully the charged prong multiplicity of the events, including very slow particles. This allowed us to study the behaviour of momenta and angles and of the negative pion multiplicity as functions of the charged prong multiplicity.

This information, together with other data both at rest and in flight, makes us conclude that there is a correlation between depth of the annihilation points and multiplicity: on average, high multiplicity means deep annihilation. We point out that recognizing deep annihilation is important, as unusual phenomena are expected to be more

probable under such conditions.

Our results agree with those obtained in other experiments and can be explained qualitatively considering $\bar{p}$ annihilation on free nucleons, using pion-nucleon rescattering and absorption with charge and baryonic number conserved.

We have compared our data with INC model calculations, although the comparison is not straightforward. Most calculations concern nuclei and/or energies other than ours, and the quantities considered are often similar but not equal to those measured in our experiment.

We have found that the gross features of the data are reproduced by the calculations (Sect. 7.2(i)). Analysis considering explicitly our results have been performed recently and reproduce them satisfactorily.

Some aspects not well accounted for by the calculations concern, for instance, the high p_T behaviour of the pion rapidity distribution; the low energy region of the pion energy distribution; backward and forward behaviour of the pion angular distribution; pion absorption and correlation between high multiplicity and deep annihilation.

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Table Captions

Tab. 1 - $\langle N_C \rangle$, $\langle n_{\pi^-} \rangle$ and $\langle n_{\pi^+} \rangle$: mean numbers of charged prongs, of π^- and of π^+ at different energies. (%) = fraction of π^- absorbed with respect to the production on ${}^2\text{H}$ (see text).

- (1) Photographic emulsion. Ekspong et al., Ref. 38. Other results: at rest $\langle N_C \rangle = 5.08$; at 300 MeV/c: $\langle N_C \rangle = 7.4 \pm 0.4$; at 400-500 MeV/c: $\langle N_C \rangle = 7.6 \pm 0.4$ (Batusov et al., Ref. 39); at 1400 MeV/c: $\langle N_C \rangle = 9.1$ (Brøivik et al., Ref. 40). (*) Ratio for π^- with energy E_C in the interval 20-80 MeV.
- (2) Bubble chamber: Agnew et al., Ref. 35. Tracks longer than 2 mm ($T > 10$ MeV if protons) were detected.
- (3) Bubble chamber: Bizzarri et al., Ref. 36. At 170 MeV the values are close to those at 57.6 MeV.
- (4) Bubble chamber: U. Amaldi et al., Ref. 41.
- (5) Streamer chamber: (a): Balestra et al., Ref. 26, (+) lower limits. The other values come from the present work.
- (6) Streamer chamber: Balestra et al., Ref. 42. $\langle n_{\pi^-} \rangle$ was measured and $\langle n_{\pi^+} \rangle$ was deduced. $\langle n_{\pi^+} \rangle$ and π^+/π^- underestimated by $\sim 5\%$.

Tab. 2 - Fraction (%) of events at rest and in flight with a number of nuclear fragments higher than the values indicated in the first column. In the 4th and 5th columns the numbers of π^- given correspond to the numbers of nuclear fragments in the 1st column.

Tab. 3 - Mean number of charged pions produced in annihilations at rest. In parentheses the mean values of the corresponding data are given. Absorption (%) = fraction of pions absorbed with respect to the production on ${}^2\text{H}$ (see text).

- a) G.T. Condo et al., Ref. 45
- b) M. Wade et al., Ref. 46
- c) L.E. Agnew et al., Ref. 35
- d) A.G. Ekspong et al., Ref. 38
- e) O. Chamberlain et al., Ref. 47 and H. Barkas et al., Ref. 48
- f) E. Amaldi et al., Ref. 49
- g) A. Berthelot et al., Ref. 50
- h) F. Balestra et al., Ref. 42
- i) T. Kalogeropoulos et al., Ref. 51

Tab. 4 - Calculated fractions (%) of pions absorbed in some nuclei at different energies compared to the Ne data. π means all pions, $\pi^\pm$ charged pions and π^- negative pions.

Figure Captions

- Fig. 1 Velocity of the center of mass of the incoming antiproton and N nuclear masses at rest for different $\bar{p}$ momenta. The velocity β is about equal to the rapidity y (see text).
- Fig. 2 (a) Full line: π^- momentum distribution from Ne at rest. Dotted line: π^- momentum distribution from the annihilation $\bar{p}n$ in deuterium [30].
(b) Momentum distribution of the nuclear fragments from Ne at rest.
- Fig. 3 Annihilation at rest, π^- . (a) Longitudinal momentum distribution. (b) Rapidity distribution.
- Fig. 4 Annihilation in flight, π^- , $\cos\theta$ distribution. Dashed line: annihilation on free protons; phase space calculation. Full line: experimental result on Ne.
- Fig. 5 Annihilation in flight, π^- , rapidity distribution. Dashed line: phase space calculation for $\bar{p}p$ annihilation. Full line: experimental result on Ne.
- Fig. 6 Annihilation in flight, π^- momentum distribution. Dashed line: phase-space calculation for annihilation on free nucleons [32]. Full line: experimental result for Ne.
- Fig. 7 Momentum distribution for the nuclear fragments from Ne.
- Fig. 8 Annihilation in flight, π^- . (a) Longitudinal momentum distribution. (b) Transverse momentum distribution.
- Fig. 9 Annihilation in flight, π^- . (a) Kinetic energy distribution. (b) Forward and backward kinetic energy distributions.
- Fig. 10 Annihilation at rest.
(a) Charged prong multiplicity distribution. On the ordinate, percentage of events.
(b) Mean number of π^- per event vs. M .
(c) For each value of M , percentage of events with 0,1,2, etc. π^- . The statistical errors are displayed for $n_{\pi^-}=1$.
(d) Mean number of nuclear fragments per event vs. M .
- Fig. 11 Annihilation in flight. The same captions as for Fig. 10.
- Fig. 12 Mean number of π^- per event vs mean number of nuclear fragments per event. (●) in flight, (○) at rest.
- Fig. 13 Full lines: π^- multiplicity distributions in ^2H [36], ^4He [37], ^{12}C [35] and photographic emulsion [38] and Ne in flight. Open dots: Ne at rest.

- Fig. 14 Mean number of stopping tracks per event vs. M . (a) Annihilation at rest; (b) in flight.
- Fig. 15 Mean π^- kinetic energy vs. M . (a) at rest (b) in flight.
- Fig. 16 Mean momentum distribution vs. M . π^- at rest (a) and in flight (b). Nuclear fragments at rest (c) and in flight (d).
- Fig. 17 Annihilation in flight. π^- mean kinetic energy vs. M . (a) forwards and (b) backwards.
- Fig. 18 Total kinetic energy carried by π^- vs. M in flight (full line) and at rest (dotted line). See text.
- Fig. 19 Ratio between the tracks emitted forwards and backwards. All tracks at rest (a) and in flight (b). π^- at rest (c) and in flight (d). Nuclear fragments at rest (e) and in flight (f).
- Fig. 20 Mean π^- longitudinal momentum vs. M in flight.
- Fig. 21 Mean $\pi^- \cos \theta$ vs. M in flight.
- Fig. 22 Annihilation in flight, π^- . (a) Mean rapidity vs. M . (b) Mean rapidity vs. p_T . (c) Rapidity distribution for $p_T < 100$ MeV/c. (d) Rapidity distribution for $p_T > 400$ MeV/c.
- Fig. 23 Nuclear fragment mean rapidity vs. M at rest (a) and in flight (b).
- Fig. 24 Annihilation at rest, π^- . Comparison between annihilation events with $M=4$ and $M=11$. Momentum, longitudinal momentum and rapidity distributions are displayed.
- Fig. 25 Annihilation in flight, π^- . Comparison between annihilation events with $M=4$ and $M=11$. Kinetic energy distributions of all π^- , of forward π^- and backward π^- are displayed.
- Fig. 26 Annihilation in flight, π^- . Comparison between events with $M=4$ and $M=11$. Distributions of momentum, longitudinal momentum, $\cos \theta$ and rapidity.
- Fig. 27 Kinetic energy distributions of π^- in flight. Full lines: experimental data. Dashed lines: calculations of Ref. 52. (a) All pions; (b) forward pions; (c) backward pions.
- Fig. 28 $\cos \theta$ distribution in flight. Full line: experimental result. Dashed line: calculation of Ref. 52.

[illegible]

TABLE 1

$\langle n_f \rangle$	% at rest	% in flight	$\langle n_{\pi^-} \rangle$ at rest	in flight
25.4	13.2	40.5	22.0	21.4
26.1	6.8	26.9	22.2	21.6
27.2	0.8	7.3	22.7	22.1

TABLE 2

	^{208}Pb 82	^{181}Ta 73	$\langle 80 \rangle_{\text{Br}}, \langle 108 \rangle_{\text{Ag}}$ 35 47	^{48}Tl 22	^{12}C 6	^4He 2	^2H 1
$\langle n_{\pi} \pm \rangle$	2.44^{a}	2.47^{a}	$2.38 \pm 0.11^{\text{d}}$ $2.90 \pm 0.26^{\text{e}}$ $2.46 \pm 0.14^{\text{f}}$ $2.54 \pm 0.17^{\text{g}}$ (2.47 ± 0.07)	2.58^{a}	2.79^{a} $2.72 \pm 0.03^{\text{b}}$ $2.85 \pm 0.22^{\text{c}}$ (2.72 ± 0.03)	$2.97 \pm 0.09^{\text{h}}$	3.05^{i} ± 0.02
(%)	20.0	19.0	19.0	15.4	10.8	2.6	---

TABLE 3

Nucleus	type of pions	at rest	100 MeV	175 MeV	References
$^{20}_{10}\text{Ne}$	π^-	15.2		22.6	This experiment
$^{12}_6\text{C}$	π^-			17.7	E. Hernandez et al. Ref. 7
	$\pi^\pm$	11.5			A.S. Iljinov et al. Ref. 1
	π^-			17.6	M.R. Clover et al. Ref. 2
	$\pi^\pm$			16.6	
	π^-			18.0	
$^{98}_{42}\text{Mo}$	π^-	16.0			J. Cugnon et al. Ref. 8
		9.0			J. Cugnon et al. Ref. 5
$^{40}_{20}\text{Ca}$	π^-		5.0		J. Cugnon et al. Ref. 4

TABLE 4

Fig.1

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Fig. 23

Fig. 24

Fig. 25

Fig. 26

Fig. 27

Fig. 28