CERN-EP/85-122
August 1st, 1985

ANTIPROTON ANNIHILATION ON Ag/Br NUCLEI

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ABSTRACT - The charged prong multiplicity distribution of ($\bar{p}$, Ag/Br) annihilation events has been measured in photographic emulsion at incoming $\bar{p}$ momenta of 500, 400, 300 MeV/c and at rest. The results show that the low multiplicity events are produced mainly by nuclear surface annihilations. The higher multiplicity events are produced in deep nuclear matter and exhibit a statistical behaviour.

(Submitted to Physics Letters)

Antiproton annihilation in photographic emulsion has been studied at rest and in flight at energies below 250 MeV by Ekspong et al.⁽¹⁾ and recently at 1.4 GeV/c by Breivik et al.⁽²⁾. In these experiments the $\bar{p}$ beam was noticeably pion contaminated. The main aim of the measurements was the study of the mechanisms of $\bar{p}$ annihilation in nuclear matter. In

particular, theoretical studies⁽³⁻⁶⁾ stress the interest of the investigation of nuclear matter under extreme temperature and pressure conditions. By using antiprotons, it is possible to induce nuclear multifragmentation and spallation reactions such as those produced in medium energy collisions of heavy ions⁽⁷⁾, but with a probe which deposits a fixed amount of energy in the nucleus.

In this paper we present the preliminary results we obtained by measuring the charged prong multiplicity distributions of the stars produced by $\bar{p}$ annihilation in photographic emulsion nuclei. The emulsion chamber consisted of 50 plates of NIKFI-BR, each of dimensions (20x10x0.06) cm³. The chamber was exposed to the 609 MeV/c ($\Delta p/p = 10^{-3}$) $\bar{p}$ beam of the LEAR facility at CERN.

In Fig. 1 the beam stopping in the central layer of the stack is shown. The range of the antiprotons, measured from the edge of the emulsion chamber, turned out to be (8.59 ± 0.13) cm, corresponding to (180 ± 2) MeV incoming beam kinetic energy, a value in fairly good agreement with the LEAR beam control data. The exposure time was about 2 sec, yielding about 2×10^5 stopped antiprotons.

Each plate of the emulsion chamber was marked⁽⁸⁾ by a 1 mm² grid and developed. Scanning and measurements were carried out by means of microscopes (magnification 1350x) with the "area method". Data concerning events produced by $\bar{p}$ -nuclei reactions were sorted out and recorded. As usually, tracks of charged secondary particles were classified as "minimum", "grey" and "black", according to their ionization. Table I shows some typical energy values in nuclear emulsion corresponding to minimum detectable lengths (1-3 μ m) for many types of particles.

The results here reported have been obtained from a study of the charged prong multiplicity distributions for antiprotons at rest and at (300 ± 11) , (400 ± 5) and (500 ± 4) MeV/c. The antiproton interactions in flight were measured at different distances from the center of the stopping region, in 2 mm depth zones, crossing the beam path shown in Fig. 1.

The data concern a total number of 1280 events of antiprotons at rest; 347 events at 300 MeV/c; 430 events at 400 MeV/c and 561 events at 500 MeV/c measured up to now.

In Fig. 2 the charged prong multiplicity distributions at the four above energies are shown.

At rest, the average value $\langle M \rangle$ of the total multiplicity is (4.9 ± 0.1) , which is close to the values obtained in ^{12}C (at rest and in flight) by Agnew et al ⁽⁹⁾ and in ^4He (in flight) by our collaboration ⁽¹⁰⁾. The highest charged prong multiplicity found at rest turns out to be 18, but the $(95 \pm 1)\%$ of the events have $M < 10$, which is also the highest value found for ^4He and ^{12}C .

For 300, 400 and 500 MeV/c antiproton momenta, the number of events with $M \geq 10$ increases in a valuable way (up to about 20%) and, consequently, so the average multiplicity does, reaching the values (7.4 ± 0.4) , (7.6 ± 0.4) and (7.6 ± 0.3) at the three momenta, respectively. These values are in agreement with the mean value 7.66 reported in Ref.(1) for antiprotons with energy in the range 10-250 MeV.

A photographic emulsion contains about 77% in weight of Ag($\bar{A} = 108$) and Br($\bar{A} = 80$) and about 23% of $^{12}_6\text{C}$, $^{14}_7\text{N}$, $^{16}_8\text{O}$. Since the $\bar{p}$ -nucleus reaction cross sections σ_R ($\sigma_R = \sigma_{\text{tot}} - \sigma_{\text{el}}$) show a very good agreement with a $A^{2/3}$ power law (See Refs.10-13), it is possible to estimate the σ_R values for all the nuclei present in a photographic emulsion. It comes out that the $\bar{p}$ interaction on the light nuclei (C, N, O) of the emulsion are about the $(28 \pm 2)\%$ of the total number of events. Moreover, taking into account the charged prong multiplicities measured in ^{12}C ⁽⁹⁾, and in ^4He and Ne by our collaboration ^(10,11), it turns out also that all these events are concentrated in the $M < 10$ region.

It is possible to conclude that all the events with $M \geq 10$ are ($\bar{p}$, Ag/Br) interactions.

Finally, since the analysis of the reaction channels in $\bar{p}$ -nucleus interaction has shown that the inelastic processes have small cross sec-

tion in comparison with annihilation's one⁽⁹⁻¹²⁾, all the non elastic events can be considered, within this approximation, as $\bar{p}$ annihilations.

We discuss the results recalling what follows. It is known that the $\bar{p}$ -nucleon annihilation cross section increases as the energy decreases. So we expect that annihilation at rest occurs mainly on the surface of nuclei and, moreover, that only about one half of the created pions (3 charged and 2 neutrals, on the average) interacts with nucleons in nuclei⁽⁴⁾.

As the incoming energy increases, correspondingly the probability increases that antiprotons penetrate deeper and deeper into nuclei and annihilate when are completely surrounded by nucleons and a higher number of pions interact with them⁽¹⁴⁾. Mechanisms different from annihilation on a free nucleon could also be present. Then, a higher amount of energy is delivered in this case, producing a higher charged prong multiplicity.

First, in Fig. 3 the four obtained multiplicity cross sections are compared with that measured at 1.4 GeV/c by Breivik et al.⁽²⁾. The areas have been normalized to the evaluated values of the reaction cross sections; only the data obtained at rest have been normalized to the same multiplicity values, in the region $M \geq 10$.

All the multiplicity distributions above 300 MeV/c display, within the statistical errors, almost the same slope for $M \geq 10$. The roughly linear dependence for high M values suggests an exponential behaviour, i.e. a statistical mechanism in the charged prong production. Tentatively, the exponential part of the multiplicity distributions has been fitted with a Maxwell distribution:

$$f(M)dM \propto \sqrt{M - M_0} e^{(M-M_0)/T} dM, \quad (1)$$

where $M_0 = 10$ and T represents the temperature (measured in M units) of the statistical production of events with high charged prong multiplicity. The formula (1) fits well all the experimental distributions, with the T values ranging within $\pm 10\%$ around the mean value.

Such a mechanism could be justified by taking into account the relative high number of particles involved in releasing a 2 GeV energy amount in $\bar{p}$ -nucleon annihilation. In each event some of this energy is shared among final state pions, nucleons and nuclear fragments; an amount E is delivered to charged particles. This latter quantity changes from event to event. If now one assumes a law of Maxwellian type and, on an average, a proportionality between E and the number of charged prongs⁽¹⁴⁾, the expression (1) will follow immediately.

Second, if we subtract from the events with $M < 10$ those on C, O and N, we obtain the total number of interaction events on Ag and Br only (all the events with $M \geq 10$ are interactions on Ag/Br). Having taken into account this correction, in Table II the relative percentages of events subtended by a fit with the Maxwellian distribution (1) at the four considered energies are reported, together with the values from Ref.(2). Surface annihilation appears to be the more probable event (and the dominant one at rest), in agreement with the $A^{2/3}$ power law behaviour found for the reactions cross sections on many nuclei⁽¹⁰⁻¹³⁾.

In Table III the average charged prong multiplicities of $\bar{p}$ surface ($M < 10$) and deep ($M \geq 10$) annihilation events in Ag/Br nuclei, together with the values from Ref.(2), are given.

The average multiplicities are close to those of the lightest nuclei, the diameters of which are comparable with the annihilation zone⁽¹⁵⁾.

In particular, at rest, the average multiplicity is very close to the value obtained in ${}^4\text{He}$ by our collaboration between 19.7 and 179.7 MeV⁽¹⁰⁾. Moreover, since the mean number of charged pions observed in annihilations on light nuclei is about 3^(1,10,16), the number of charged heavy particles involved in the interaction is at rest only 2-3, on the average. This indicates that there is a no significant interaction among nuclei, pions and other particles produced in $\bar{p}$ -nucleon annihilation, as it is expected in the case of annihilations on the nuclear surface⁽⁴⁾.

For annihilations in flight, the mean number of charged prongs with $M < 10$ is not far from the corresponding value for the at rest events, in-

dicating that also in flight events with $M < 10$ occur mainly on the nuclear surface.

Finally, in Fig. 4 the distribution of the nuclear matter density $\rho(r)/\rho(0)$ of Ag/Br nuclei is shown together with the $\bar{p}$ absorption probabilities P_{abs} calculated by Clover et al.⁽¹⁴⁾ for 590 MeV/c antiprotons (with two values, 0 and 250 MeV, for the real $\bar{p}$ -nucleus attractive potential) and by Iljinov et al.⁽⁴⁾ for antiprotons at rest. In the first case, the P_{abs} maximum value occurs about in the 0.5 $\rho(0)$ density region, while the $\bar{p}$ annihilation probability in the region $\rho(r) > 0.75 \rho(0)$ amounts to within 14-27% over the total number of events. This figure is in very good agreement with the percentage of deep annihilations at 500 MeV/c, from the fit of the experimental data, reported in Table II.

In the case of $\bar{p}$ at rest, the $(P_{abs})_{max}$ occurs in the 0.1 $\rho(0)$ region, while the $\bar{p}$ annihilation probability in the $\rho(r) > 0.75 \rho(0)$ region is about 5% over the total number of events, again in very good agreement with the value quoted in Table II.

At this point, it seems possible to conclude that two mechanisms can be distinguished in $\bar{p}$ annihilation in medium and heavy nuclei:

- a) Annihilation on the nuclear surface, with production of events with an average multiplicity of (4.5 ± 0.1) , the relative number of which increases at low antiproton energies. Also the σ_R values increase at lower energies, as in the case of $(\bar{p}, N)$ interaction, indicating that the main mechanism of surface annihilation is annihilation on a quasi-free nucleon, which is the dominant absorption mechanism at rest.
- b) Annihilation in the deep nuclear matter, in the more dense region of nucleus, with production of events with an average multiplicity of (13.2 ± 1.5) , the relative number of which increases with the $\bar{p}$ kinetic energy. These events show that they are produced by a mechanism different from annihilation on a quasi-free nucleon, since reaction cross sections for $M \gtrsim 10$ are independent of energy.

The study (in progress) of angular and range distributions of secondary particles can help the understanding of the intriguing problems

of nuclear multifragmentation, in a parallel way to the studies performed through medium and high energy collisions of heavy ions.

We thank the LEAR machine group for the essential support. We are grateful to V.P.Dzhelepov and B.Pontecorvo for their constant interest.

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FIGURE CAPTIONS

Fig. 1 - Antiproton beam stopping in the central layer of the emulsion chamber.

Fig. 2 - Charged prong multiplicity distributions of $\bar{p}$ reaction events in nuclear emulsion. The average values of the total multiplicity are also given.

Fig. 3 - Multiplicity cross sections for $\bar{p}$ interaction in nuclear emulsion. The data at 1400 MeV/c are from Ref.(2); all the other data are from the present experiment. The full line represents a fit performed with the Maxwell distribution (1) of the ($\bar{p}$, Ag/Br) interaction events.

Fig. 4 - Probability of $\bar{p}$ annihilation in Ag/Br nuclei vs the nuclear radius. The histogram is a calculation by Clover et al ⁽¹⁴⁾ for 590 MeV/c $\bar{p}$ (the solid curve corresponds to a $\bar{p}$ -nucleus potential $V = 250$ MeV, the dashed curve corresponds to $V = 0$). The full line is a calculation by Iljinov et al ⁽⁴⁾ for $\bar{p}$ at rest.

TABLE CAPTIONS

Table I - Range-energy values in nuclear emulsion for minimum detectable lengths ($1-3\ \mu\text{m}$).

Table II - Relative percentages of $\bar{p}$ annihilation events occurring on the surface or deep inside the nuclear matter of Ag/Br nuclei according to the charged prong multiplicity M . The values have been obtained by a fit with the distribution (1) of the data from this experiment and from Ref.(2). The fit error has been estimated to be about 12%.

Table III - Average charged prong multiplicities $\langle M \rangle$ of $\bar{p}$ surface and deep annihilation events in Ag/Br nuclei. The data are from this experiment and from Ref.(2).

TABLE I

Particles or nuclear fragments	$L = 1 \mu\text{m}$ (MeV)	$L = 3 \mu\text{m}$ (MeV)
p	0.071	0.215
d	0.094	0.283
t	0.104	0.312
α	0.285	0.857
^{12}C	0.833	3.428
^{16}O	1.400	4.833
^{20}Ne	2.000	6.250

TABLE II

$\bar{p}$ momentum (MeV/c)	Surface annihilation ($M < 10$)	Internal annihilation ($M \geq 10$)
at rest	93 ± 1	7 ± 1
300	71 ± 5	29 ± 5
400	74 ± 4	26 ± 4
500	72 ± 4	28 ± 4
1400 ⁽²⁾	63 ± 3	37 ± 3

TABLE III

$\bar{p}$ momentum (MeV/c)	Surface annihilation ($M < 10$)	Internal annihilation ($M \geq 10$)
at rest	4.5 ± 0.1	12.8 ± 1.6
300	5.9 ± 0.4	12.9 ± 1.5
400	6.1 ± 0.3	13.5 ± 1.5
500	6.1 ± 0.3	13.1 ± 1.2
1400(2)	6.3 ± 0.2	13.9 ± 0.7

F.Balestra et al;

FIG. 1

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FIG. 2

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FIG. 3

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