EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/85-79
May 21st, 1985

LOW ENERGY ANTIPROTON ANNIHILATION ON NUCLEI

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ABSTRACT - Data obtained in the study of the antiproton interaction on ⁴He, Ne and photographic emulsion nuclei are reported. Charged prong multiplicities, branching ratios and reaction cross section values are given. Some features of $\bar{p}$ annihilation deep inside the nuclear matter are described.

INTERNATIONAL CONFERENCE ON ANTINUCLEON- AND NUCLEON-NUCLEUS INTERACTIONS
Telluride, Colorado, March 18-21, 1985.

The results obtained by our collaboration in the PS179 experiment at CERN are presented. We have studied the $\bar{p}$ interaction with ^4He and Ne nuclei at three momenta 201, 308, 609 MeV/c. In the future, measurements will be performed at lower $\bar{p}$ energies and on the lighter nuclei ^2H and ^3He . Also $\bar{p}\text{Ag/Br}$ annihilation events in a stack of nuclear emulsions have been studied at rest and in flight at 500, 400, 300 MeV/c.

Our apparatus consists of a 113 litres self shunted streamer chamber, in a magnetic field, filled at 1 atm with gas targets¹. The possibility to measure short nuclear fragment ranges (corresponding to energies lower than 1 MeV) together with the curvature of the fast particles (only in the streamer chamber) and the very good vertex resolution allow us to obtain the best determinations of the charged prong multiplicity available at present. In fig.1 the values of the reaction cross section ($\sigma_R = \sigma_{\text{tot}} - \sigma_{\text{el}}$), which we measured directly, are com-

Fig.1-Reaction cross section behaviours for different nuclei: Δ -ref.5; $\diamond$ -ref.6; $\bullet$ -ref.3; $\blacksquare$ -ref.2; $\cdots$ -ref.4; $-\cdot-$ ref.7; $\circ$ -present data.

Fig.2-Reaction cross sections vs $A^{2/3}$: $\circ$ -ref.6; $\blacksquare$ -ref.5; $\bullet$ -present data.

pared with those deduced for different nuclei by other authors²⁻⁶) (see also the Garreta's contribution to this conference). As one can see, our data at 201 MeV/c are those obtained at the lowest $\bar{p}$ momentum reached up to now and the σ_R energy behaviours are similar to that of the $\bar{p}p$ interaction. Dalkarov and Karmanov showed that⁸) the $\bar{p}^{12}\text{C}$ elastic scattering data⁶) at low energy are well described by the Glauber approximation⁹). In fig.2 the σ_R values are plotted vs $A^{2/3}$ and, using the same parameters of ref.8, we obtained also good agreement with the experimental values. These behaviours of σ_R show that the nuclei, in terms of the optical model, are black to antiprotons and that the $\bar{p}$ interaction occurs mainly on the nuclear surface. In fig.3 the charged prong multiplicity distributions obtained for ^4He at 201, 308 and 609 MeV/c are shown. The even prong events are $\bar{p}$ annihilations on a neutron with ^3He recoil. The reaction cross section values are (406 ± 16) , (294 ± 9) and (233 ± 7) mb respectively.

Fig.3-Distribution of the charged prong multiplicity M for $\bar{p}^4\text{He}$ interaction.
Fig.4-Charged prong multiplicity cross sections for $\bar{p}\text{Ne}$ interaction.

These values show an energy behaviour very similar to that of the $\bar{p}p$ interac-

tion (see the Ransome's contribution to this conference), suggesting the hypothesis of $\bar{p}$ annihilation on quasi-free nucleon as main mechanism of $\bar{p}^4\text{He}$ interaction. It must be noted that at 19.6 MeV (where only annihilation is possible) the 2- and 3- prong events percentages are the same as at higher energies, within the experimental errors. This fact shows that the knock-out reaction contributions are small, as in the case of the inelastic scattering⁶). In other terms the non elastic reactions, with the $\bar{p}$ present in the final state, have much less probability to occur than the annihilation reactions. The average value of the charged prong multiplicity M is constant and the values are (4.0 ± 0.2) , (4.0 ± 0.1) and (4.1 ± 0.1) at 201, 308 and 609 MeV/c, respectively. In fig.4 the behaviours of the cross section values of the multiplicities measured for the $\bar{p}\text{Ne}$ non elastic events at the same energy values as for the helium are shown. The σ_R values are (956 ± 47) , (771 ± 28) and (627 ± 21) respectively. As one can see the distributions are formed by two regions, in the first, the events with $M \leq 9$ have average multiplicities (5.8 ± 0.3) , (5.8 ± 0.2) and (5.9 ± 0.2) and are characterized by the increasing of the cross sections at the decreasing of the $\bar{p}$ kinetic energy. In the second region, with $M > 9$ and average multiplicities (10.7 ± 1.6) , (10.7 ± 1.1) and (10.8 ± 1.0) , the cross section values are independent of the energy, indicating, for this kind of events, a reaction mechanism in which the $\bar{p}$ kinetic energy is negligible in comparison with the energy released in the nucleus by the annihilation. Moreover, the multiplicity distributions show a statistical behaviour for high M values. Tentatively a fit has been performed with the Maxwell distribution:

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

for $M_0 = 9$, of the experimental data. The percentages of the high multiplicity events subtended by the (1) are $(13 \pm 2)\%$, $(16 \pm 1)\%$ and $(20 \pm 1)\%$ at the three energies, respectively. That is, the cross sections for these events are constant, but their percentage increases with the energy, suggesting the hypothesis of events produced by $\bar{p}$ annihilations deep inside the nuclear matter. On the other hand, the cross sections of the lower multiplicity events ($M \leq 9$) increase with

the decreasing of the $\bar{p}$ energy, as in the case of the σ_R and $\sigma(^3\text{He})$ values for the $\bar{p}^4\text{He}$ interaction and also for the $\bar{p}p$ interaction, suggesting for these events, as main reaction mechanism, the $\bar{p}$ annihilation on quasi-free nucleons of the nuclear surface. Moreover, the percentages of these events are high: $(87\pm 4)\%$, $(84\pm 3)\%$ and $(80\pm 3)\%$ at 201, 308 and 609 MeV/c, respectively. The dominance of the surface annihilation mechanism explains the $A^{2/3}$ power law behaviour of the reaction cross sections (see fig.2). Similar conclusions can be drawn from the data obtained by analyzing the $\bar{p}\text{Ag}/\text{Br}$ annihilation events. The emulsion chamber, exposed for 2s at the LEAR $\bar{p}$ beam of 609 MeV/c ($\Delta p/p \approx 10^{-3}$), consisted of 50 plates of NIKFI-BR emulsion each of the dimension $(10 \times 5 \times 0.06) \text{ cm}^3$. In this contribution we present the preliminary results obtained from a study of the total charged prong multiplicity distributions by measuring, for $\bar{p}$ at rest and at (300 ± 11) , (400 ± 5) , (500 ± 4) MeV/c, 1280, 347, 430 and 561 events, respectively. At rest the average value of the total multiplicity is (4.9 ± 0.1) , which is close to the values obtained for the ^{12}C (at rest and in flight) by Agnew et al.¹⁰) and in ^4He (in flight) by our collaboration. The maximum M value found at rest is 18, but the $(93\pm 1)\%$ of the events have $M \leq 10$, which is also the maximum M value found for ^4He and ^{12}C . For $\bar{p}$ with 300, 400 and 500 MeV/c, the relative number (see fig.5) of events with $M > 10$ increases noticeably and, consequently, so does the average value of the total multiplicity which is (7.4 ± 0.4) , (7.6 ± 0.4) and (7.6 ± 0.3) at the three momenta, respectively. The energy behaviour of the $\bar{p}$ -nuclei reaction cross section shows a very good agreement (see fig.2) with the $A^{2/3}$ power law, so that it is possible to estimate the σ_R values for all the nuclei present in the photographic emulsion. Then, taking into account the emulsion composition, it is possible to deduce that the events of $\bar{p}$ interaction on emulsion light nuclei (^{12}C , ^{14}N , ^{16}O) are about $(28\pm 2)\%$ of the total number of events and, taking into account the M measurements for the ^{12}C of ref.10 (and for He and Ne our collaboration), that those events are concentrated within the $M \leq 10$ events regions. Therefore all the events with $M > 10$ are $\bar{p}\text{Ag}/\text{Br}$ interactions (Ag with $\bar{A}=108$ and Br with $\bar{A}=80$).

Fig.5-Charged prong multiplicity distribution of $\bar{p}$ annihilation events in nuclear emulsion.

Fig.6-Multiplicity cross sections for $\bar{p}$ Ag/Br interactions. The data at 1.4 GeV/c are from ref.11. Full line:fit with the (1).

Moreover, the analysis of the non elastic channels showed that the inelastic and knock-out interactions are very small in comparison with the annihilation channel, which dominates the reaction cross section. Within these approximations, all the non elastic events can be considered as $\bar{p}$ annihilations. In Fig.6 the M distributions we obtained are compared with that measured at 1.4 GeV/c by Breivick et al¹¹); the areas have been normalized to the evaluated values of σ_R , only the data obtained at rest have been normalized to the same M values, in the region with $M \geq 10$. Tentatively (as in the case of the Ne data) the distributions have been fitted using the distribution (1), with $M_0=10$. At this point, it seems possible to conclude that two mechanism can be distinguished also in the $\bar{p}$ annihilation in Ag/Br nuclei:

a) $\bar{p}$ - $\bar{p}$ annihilation on the nuclear surface, with production of events with average multiplicity of (4.5 ± 0.1) , the relative number of which increases at low $\bar{p}$ energies. Also the σ_R values increase at lower energies, as in the case of $\bar{p}N$ reaction cross section, indicating that the main mechanism of annihilation on the surface is that of annihilation on quasi-free nucleon and it is the most important absorption mechanism for $\bar{p}$ at rest.

b) $\bar{p}$ - $\bar{p}$ annihilation in the nuclear matter, deep inside the nucleus in a denser region, 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 hypotheses are in very good agreement with those made to explain qualitatively the $\bar{p}$ annihilation in flight in Ne.

In fig. 7 the distribution of the nuclear matter density $\rho(r)/\rho(0)$ of Ag and Br nuclei is shown and compared with the $\bar{p}$ absorption probability P_{abs} , calculated by Clover et al.¹⁷⁾ for 590 MeV/c antiprotons (with two values, 0 and 250 MeV, of the real $\bar{p}+A$ attractive potential) and by Iljinov et al.¹³⁾ for $\bar{p}$ at rest. In the first case, the P_{max} value occurs approximately in the 0.5 density region and the probability of $\bar{p}$ annihilation, in the region $\rho(r) > 0.75\rho(0)$, amounts to $14 \pm 27\%$ of the total number of events, in good agreement with the percentage of annihilations in the depth of the nuclei we estimated in table I at 500 MeV/c. In the case of $\bar{p}$ at rest, the P_{max} occurs in the $\rho(r) \approx 0.1\rho(0)$ region¹³⁾ and the probability of $\bar{p}$ annihilation in the region $\rho(r) > 0.75\rho(0)$ is about 5% of all the events, in good agreement with the value we estimated in table I. In fig. 8 the distribution of the nuclear matter density of the Ne is compared with the absorption probability calculated by Clover et al.¹⁷⁾ for light nuclei, also in this case we obtained a good agreement between the percentage we estimated of deep annihilations for the Ne and that calculated in ref. 17 of annihilations occurring in the density region $\rho(r) > 0.75\rho(0)$.

Table I-Percentages of $\bar{p}$ annihilations occurring in the nuclear surface or deep inside the nuclear matter of Ag/Br nuclei. The fit errors with (1) are estimated of about 12%.

$\bar{p}$ momentum (MeV/c)	Surface ann. ($M < 10$)	Deep ann. ($M > 10$)
at rest	93 ± 1	7 ± 1
300	71 ± 5	29 ± 5
400	74 ± 4	26 ± 4
500	72 ± 4	28 ± 4
$1400^{11)}$	63 ± 3	37 ± 3

Fig.7-The probability of $\bar{p}$ annihilation in Ag/Br vs the radius of annihilation¹⁷⁾. The solid curve results from calculations with $V=250$ MeV, the dashed curve with $V=0$.

Fig.8-The probability of $\bar{p}$ annihilation in Ne vs the radius of annihilation¹⁷⁾. The curve are the same as in fig.7

It is possible to conclude that the $\bar{p}$ interacts with the nucleus surface (elastic scattering) or with a quasi-free nucleon of the surface (annihilation). Moreover there are also events, with high prong multiplicity, produced by deep annihilation inside the nuclear matter involving more than one nucleon; these events are generically named "fireballs"¹²⁻¹⁶⁾. The measurement (in progress) of the secondary particle angular and energy distributions will help the investigation of nuclear matter in extreme temperature and pressure conditions and also the understanding of the intriguing problem of nuclear multifragmentation

in parallel with the studies performed on the high and medium energy collisions of heavy ions.

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