LOW ENERGY ANTIPROTON NEON INTERACTION

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Abstract

By means of a streamer chamber exposed to the LEAR antiproton beams, the total reaction cross sections, the charged prong multiplicity distributions and lower limits for the production of negative pions and K_g^0 in the $\bar{p}$ Ne interaction were measured at 19.6, 48.7 and 179.6 MeV. Annihilation was found to be dominant over all other non elastic $\bar{p}$ Ne processes. An analysis of Ne and other nuclei data in the frame of Glauber theory allowed to determine the ratio between the $\bar{p}$ -neutron and the $\bar{p}$ -proton cross sections. An analysis in the light of INC model predictions allowed to show up events which can be interpreted as annihilations occurred deeply inside the nuclei.

1. Introduction

In the last years many theoretical studies have been devoted to the interaction of low energy antiprotons with atomic nuclei in order to understand the nature of the forces between $\bar{p}$ and free and bound nucleons, the annihilation mechanism and the properties of the nuclear matter in a highly excited state, which is expected in the release of 2 GeV by the annihilation process. Recently some new experimental data appeared [1-8], which can be compared with the above speculations. The present paper intends to contribute to this field with data on the $\bar{p}\text{Ne}$ interaction concerning total reaction cross-sections, charged prong multiplicities and lower limits for the negative pion production and for the $\bar{p}\text{Ne} \rightarrow V^0 + X$ reaction at the energies of 19.6, 48.7 and 179.6 MeV.

These results were obtained by taking advantage of two features of our apparatus, the visualizing technique and the low density of the gas target, which allow to see distinctly the vertices of the events, to detect very slow particles and to determine the reaction cross sections without any model dependent corrections.

Data taking conditions and scanning criteria were similar to those we used for the study of the $\bar{p}^4\text{He}$ interaction [1]. They are summarized in Sect. 2 and 3. In Sect.4.1 our results on the $\bar{p}\text{Ne}$ total reaction cross section are reported and compared with similar data on other nuclei. In Sect.4.2 all these data are analyzed in the frame of the Glauber theory to find the ratio between the $\bar{p}$ -neutron and $\bar{p}$ -proton cross sections. In Sect.4.3 the charged prong and negative pion multiplicity distributions are given. They are commented in the light of theoretical predictions in Sect.4.4, making annihilations occurred deeply inside the nucleus evident. Sect.4.5 gives information on the K_g^0 production.

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.[2]. The chamber, having a sensitive volume of $70 \times 90 \times 18 \text{ cm}^3$, was filled with natural neon (90.29% of ^{20}Ne and 8.83% of ^{22}Ne) at about 970 mbar and 25 °C. Temperature and pressure were measured during each data taking and their relative variations did not exceed a few parts per thousand. The effective beam energies used were estimated to be 19.6, 48.7 and 179.6 MeV (192.8; 306.2; 607.7 MeV/c, respectively). The magnetic field was 0.415, 0.630 and 0.805 T, respectively, at the three energies.

3. Event and prong recognition.

The results here reported were obtained by simply counting the non elastic interactions (i.e. annihilation, nuclear fragmentation and charge exchange) and the charged prongs, distinguishing the negative particles from the positive ones. The reaction $\bar{p} + {}^4\text{He} \rightarrow V^0 + X (V^0 = K^0, \Lambda)$ was identified through the decay modes.

The detection efficiency of the chamber was determined through repeated measurements. It turned out to be about 100% for those events the vertices of which were occurring in the 80 cm long central region of the chamber. Such a high efficiency was due to the presence of only one event per photograph, a fact which makes very easy the vertex recognition. In measuring the total charged prong multiplicity the fiducial region was reduced to a 55 cm long central zone, far from the chamber walls, so as to maintain the same detection efficiency for prongs emitted both in the forward and backward direc-

tions.

In this region 412 events were produced by $3.33 \cdot 10^5 \bar{p}$ at 19.6 MeV, 760 events by $7.69 \cdot 10^5 \bar{p}$ at 48.7 MeV and 870 events by $1.07 \cdot 10^6 \bar{p}$ at 179.6 MeV.

Obviously, we can detect only charged particles which have an energy sufficient to produce visible prongs in the chamber. Considering the presence of background consisting of ionization blobs and secondary ionization effects, it results that some events with prongs shorter than 2-3 mm have an ambiguous multiplicity. We notice that a range of 0.4 cm in Ne may correspond, for example, to a 0.8 MeV alpha-particle or to a 0.3 MeV proton. We assigned to these events the most probable multiplicity value resulting from repeated scanning procedures and we included them in the final data. Different scanners assigned the same number of charged prongs to the same event in 93% of the cases. In the other cases the uncertainty was of ± 1 prong. Nevertheless, it is worth emphasizing that the detector used allows to get the most accurate determination of the charged prong multiplicities at present obtainable.

There is very poor experimental information on specific non elastic channels other than annihilation. The cross-section for charge exchange on free proton ranges from 16.5 mb at 200 MeV/c to 12 mb at 600 MeV/c [3,4] and it was found lower by a factor 0.86 on ^{12}C at 600 MeV/c [5], the total reaction cross section being 500 mb [6,7]. The cross section for the excitation of the 4.4 MeV level in ^{12}C at 300 MeV/c was found of the order of 7 mb, against a total reaction cross section of 600 mb [8]. The neutron knock-out process $^{12}\text{C}(\bar{p}, \bar{p}n)^{11}\text{C}$ at 1.73 GeV was studied in ref.[9] and for its cross section an upper limit of 28.2 mb (about 10% of the reaction cross section value) was measured. $\bar{p}$ -nucleus quasi-free elastic scattering was found to be negligible [10]. These results, which agree with our previous data on $\bar{p}^4\text{He}$ interaction [1] too, show

that these processes contribute to the total reaction cross section by less than 5% and that annihilation is the dominant process.

We analyzed all non elastic processes with the exclusion of neutron knock-out events, the distinction of which from the elastic scatterings requires the measurement of the angles and momenta of the particles involved. For the same reason also the inelastic scattering events with excitation of the residual nucleus were not considered.

Nuclear fragmentations are characterized by only one negative particle in the final state (the scattered antiproton). Moreover, at the lowest energy we used (19.6 MeV), the possible nonelastic reactions different from annihilation are only those listed in table 1, which have no more than three heavy positive particles among the final products. These facts set strong limitations on the possible presence of antiprotons among the negative particles, which are mostly negative pions.

Depending on the deep angle of the prongs, there are some cases in which it is not possible to determine the curvature of the tracks. This fact allows us to give only a lower limit for the production of negative pions.

The V^0 (K_g^0 and Λ) were recognized through their decay mode into a pair of charged particles. Since we worked at energies where the Λ production is possible only in rare processes as the annihilation on two nucleons (see also sect.4.4), we assumed that all the V^0 are K_g^0 decays. Taking into account the mean life and the experimental momentum distribution for the kaons produced in $\bar{p}p$ annihilation, we deduced that 44% of K_g^0 decays within 1 cm from the vertex of the annihilation events and 100% decay within 10 cm, i.e. all K_g^0 decay in the streamer chamber volume. In the present work we deduce only the lower limit for the K_g^0 production rate, without any correction for the scanning efficiency.

4. Results and comments.

4.1 Total reactions cross sections.

The total reaction cross section values are given in table 2. These values are lower limits because the small contributions from the inelastic scattering ($\bar{p}, \bar{p}'$) and from the fraction of non elastic reactions with $\bar{p}$ present in the final state not distinguished from elastic scattering are not included. However, on the basis of the discussion of the previous section, this cross section defect is less than 5%. The errors quoted are statistical. A systematic error of 2.5%, due to uncertainties on the target transparency and on the beam counting, must be considered too.

Since the reaction cross sections σ_R are proportional with very good approximation [6,11] to $A^{2/3}$, we can easily deduce from the cross sections measured for the isotopic mixture of natural neon (90,92% ^{20}Ne , 0.26% ^{21}Ne , 8.82% ^{22}Ne) the cross sections for the most abundant isotope ^{20}Ne . These values differ very little from the experimental ones and are reported in parenthesis in tab.2.

In figs.1 and 2 the Ne cross section values are compared with the ^4He values [1] (obtained with the streamer chamber too) and with data, concerning other nuclei, deduced from elastic scattering measurements [7,8] and from a transmission experiment [6].

4.2 Glauber theory analysis of the reaction cross sections.

The behaviour of σ_R with the incident momentum is similar for all nuclei and follows that of the $\bar{p}$ -p interaction. This suggests a diffractive picture where the dominant reaction mechanism is the $\bar{p}$ annihilation on quasi free nucleons and the differences in σ_R among the nuclei are explainable in terms of shadow effects, which reduce the probability that a target nucleon is "seen" by the incident antiproton. For these rea-

sons, the $\bar{p}$ -nucleus low energy interaction has been discussed recently, in a number of papers [12-15], in the framework of the diffraction approximation (Glauber theory). These analyses have shown that, due to the strong absorption of $\bar{p}$ into the nucleus and to the consequent forward-peaked nature of the $\bar{p}$ nucleus elastic scattering amplitude, there are no sources of big violation of this approximation down to momenta of 300 MeV/c.

Moreover, we recall that the Glauber theory is exact in the eikonal first order expansion, because of the complete cancellation between off-shell effects and rescattering terms [16-18]. Hence, the relative size of the first order corrections, arising from noneikonal effects, are $\sim [\text{Re}f(0)/(\text{KRI}\text{Im}f(0))]^2$ on the total cross section and $\sim (q^2 R/8K)^2$ on the differential elastic cross section [12,19]. Here K is the incident momentum, R the nuclear radius, q the transferred momentum and $f(0)$ the $\bar{p}$ -nucleon elastic scattering amplitude. Since in the low energy $\bar{p}$ -nucleus scattering $\text{Re}f(0)/\text{Im}f(0) \lesssim 0.2$ and the elastic scattering distribution is forward-peaked, these corrections are negligible on σ_R and affect the differential elastic cross section by less than 5% for all the angles measured down to momenta of 300 MeV/c.

On the basis of these results, and following previous analyses of $\bar{p}^2\text{H}$ data [12], we used the Glauber theory for obtaining the $\bar{p}$ -neutron scattering parameters from $\bar{p}$ -nucleus cross sections. We started from the standard Glauber theory [20] and solved numerically the integrals which give the $\bar{p}$ -nucleus elastic scattering amplitude $F(\theta)$. As in ref.[20], we used, for the light nuclei ($A \leq 16$), the point nucleon densities given by the harmonic oscillator wave functions, and, for the heavier nuclei ($A > 16$), Woods-Saxon densities. For $A \leq 16$ the radii of these densities were obtained by applying to the charge distribution radii reported in ref.[21] the well known

formulae of ref.[22]. The radius r and the diffuseness a of the point Woods-Saxon densities were taken from ref.[23] ($r=1.158$ fm, $a=0.397$ fm). The geometry of the nucleon centers being fixed, we obtained $F(\theta)$ as a function of the six parameters σ_J , β_J (the index J stands for proton ($J=p$) and neutron ($J=n$)). They are defined by the usual expression of the $\bar{p}$ -nucleon elastic scattering amplitude at the laboratory momentum K :

$$f_J(q) = (K/4\pi) \sigma_J (i + \epsilon_J) e^{-\beta_J^2 q^2/2}$$

where q is the transferred momentum, $\epsilon_J = \text{Re}f_J(0)/\text{Im}f_J(0)$ and σ_J is the $\bar{p}$ -nucleon total cross section. Then, defining $R = \sigma_n / \sigma_p$ and supposing this ratio to be valid also for the total elastic $\bar{p}$ -nucleon cross section, we obtained $R = \beta_n^2 / \beta_p^2$ for $\sigma_n, \sigma_p \ll 1$ (see ref.[12]). In this way, taking for σ_p , and σ_p the values measured in $\bar{p}p$ scattering experiments [24-27] and assuming $\epsilon_p = \epsilon_n$, we obtained a theory where only R is a free parameter.

The Coulomb interaction was included in the calculations [20] and σ_R was calculated following the formulae of refs. [28] and [29].

The parameters utilized are reported in table 3 and the results of the fit are shown in fig.2. We note that these curves have an irregular behaviour in the light nuclei region (not drawn) and show a linear dependence on $A^{2/3}$ when A increases. Moreover, they are insensitive to the change of σ_p and σ_n within the values above mentioned. At 600 MeV/c we obtained $R=0.94 \pm 0.04$, a result in agreement with the value $R=1.01 \pm 0.05$ found in the analysis of $\bar{p}^2\text{H}$ data at the same energy [12].

At 300 MeV/c we obtained $R=0.76 \pm 0.06$ in agreement with the result $R \approx 0.8$ found in a previous analysis [15] of $\bar{p}^{12}\text{C}$ data [8] and $\bar{p}^2\text{H}$ data [30] at the same energy. We note that

the value $R \sim 0.7$ fits well also our ${}^4\text{He}$ and Ne data at 200 MeV/c, even if in this case the validity of the Glauber theory is questionable.

We recall also that the analysis of ref.[14] of the $\bar{p}{}^2\text{H}$ data around 300 MeV/c of ref.[31] gives for R a higher value ($R \sim 1.34$), but this discrepancy reflects the disagreement between the data on ${}^2\text{H}$ of refs.[30] and [31].

Finally, by using the parameter set of table 3, we calculated the $\bar{p}{}^{12}\text{C}$ elastic scattering distributions at 300 and 600 MeV/c. The agreement with the data of ref.[7,8] is remarkable (see figs.3 and 4), considering also that in this case we have not used free parameters. We note that the agreement between the data and our calculations is good in spite of the absence in the theory of spin and nuclear excitation effects, a fact which is a consequence of the strong dominance of the annihilation channel in the $\bar{p}$ -nucleus interaction.

4.3 Charged prong multiplicities.

The information we obtained on the charged particles emitted in the $\bar{p}\text{Ne}$ interaction is summarized in fig.5 and tables 2, 4 and 5. Fig.5a shows the reaction cross section $\sigma_R(M)$ vs. the charged prong multiplicity M at 19.6, 48.7 and 179.6 MeV. The quoted errors are statistical; also a systematic error less than about 7%, due to uncertainties in the prong multiplicity measurements, was estimated.

Fig.5c shows the mean number of stopped particles per event ($\langle n_g \rangle$); they are the particles going to rest within the sensitive volume of the chamber (for instance, protons with kinetic energy in the 2-5 MeV interval).

Fig.5d shows the mean number of π^- per event $\langle n_{\pi^-} \rangle$ vs M and table 5 gives the π^- multiplicity distribution at the three energies. The negative particles include both antipro-

tons and negative pions (We neglect Kaons here). However, antiprotons are present only in nuclear fragmentation events and we recall that at 19 MeV these events have no more than four charged prongs; therefore for $M > 4$ all events are annihilations and all negative particles are pions. On the other hand, from fig.5d and tables 2 and 5 we see that there is no difference in the negative particle distributions at the three energies and for any M , so that, at a first approximation, we may consider all the negative particles as negative pions. This fact gives a further support to the assumption that the events with an antiproton present in the final state are of minor importance in the $\bar{p}\text{Ne}$ interaction.

Now we summarize the most significant aspects of the experimental data.

- a) The total reaction cross section increases strongly as the energy decreases, similarly to the $\bar{p}$ -nucleon cross section.
- b) For $M > 9$, the cross sections at the three energies are equal within the experimental errors (see table 2).
- c) At each energy there is a substantial fraction of events with a number of charged prongs comparable with the atomic number of Ne or higher than it (12-15% of events with $M > 9$).
- d) The percentage of events with $M > 9$ increases with energy. The percentage P vs. M , expressed by the formula $\sum_i G_i(i > M) / G_R$, is sketched for 19.6 and 179.6 MeV, respectively, in fig.5b.
- e) High multiplicity events have a higher mean number of pions.
- f) On the base of $\bar{p}^2\text{H}$ and $\bar{p}^{12}\text{C}$ data [32,33] and intranuclear cascade model calculations [34], we expect a ratio $\pi^+ / \pi^- \simeq 0.75$. Hence, for $M > 9$, as $\bar{M}$ is about 10.7 and $\langle n_{\pi^-} \rangle$ is 1.75, the heavy prongs must be $10.7 - (1.75 \times 0.75 + 1.75) = 7.5$ on the average, so that the nuclei which have atomic number 10 are disintegrated mostly into free nucleons. This means that an energy greater than the binding energy was transferred to the nucleons.

g) In a semilogarithmic histogram (see fig.6) all the multiplicity distributions display, within the statistical errors, almost the same slope for $M > 9$. The roughly linear dependence on M 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:

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

where T represents the temperature (measured in M units) of the statistical production of events with high charged prong multiplicity. At 300 MeV/c this formula fits well the experimental distribution with $T=0.87$, $M_0 = 9$ and $\chi_r^2 = 1.2$ (see fig.6). Similar results were obtained at the other energies too.

The statistical 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 the charged particles. This latter quantity changes from event to event according to a law which can be supposed to be of Maxwellian type. If one assumes, on the average, a proportionality between E and the number of charged prongs [34], the above expression follows immediately.

4.4 Comparison with theoretical predictions.

Now we discuss our results in the light of some theoretical predictions coming mainly from the so called Monte Carlo intranuclear cascade (INC) models [34-40].

Very schematically, annihilations are expected to occur on the surface of the nucleus or deeply inside the nucleus. In

the first case the cross section is expected to follow the energy behaviour of the $\bar{p}$ -nucleon reaction cross section, which increases as the energy decreases. A quite different behaviour vs. energy is expected for the annihilations inside the nucleus due to Pauli blocking, Fermi motion and the attraction produced by the Coulomb and nuclear potentials [36]. In particular, the strong attractive real potential increases the $\bar{p}p$ and $\bar{p}n$ relative momentum so that the effective free cross section inside the nucleus is smaller than that on the surface. In ref.[36] it is also shown that the penetration of antiprotons into the nucleus changes little with energy, although the cross section increases rapidly at low energy. This should explain quantitatively the different behaviours of the total reaction cross section for $M < 9$ which increases strongly as the energy decreases and is proportional to $A^{2/3}$ and of the cross section for $M > 9$, which is constant (see table 2 and figs. 1 and 2).

In INC models, at each annihilation event, pions are generated at random according to the multiplicities and momenta known from data and models on $\bar{p}$ -nucleon annihilation. The interaction of the pions with the residual nucleus is described in terms of a cascade of π -nucleon and nucleon-nucleon interactions generated with Monte Carlo techniques. The pions interacting more strongly with the nucleons via the Δ resonance are those arising from annihilations with production of 4, 5 and 6 pions (see ref.[37]). Most of them interact elastically, and only a few per cent is absorbed. In the case of in flight annihilations, the pions transfer a greater lot of energy to the nucleus if the annihilation is deep and if they are emitted backwards.

The models predict significant correlations among the depth of the annihilation point, the number of interacting pions, the energy transferred to the nucleons and the number of excited nucleons.

Hence, in the presence of deep annihilations, one should observe a high number of charged particles in the final state (nuclear fragments and pions) correlated with an excess of slow pions. Moreover this effect should be rather invariant with the energy. This is just what shows up from fig.5 and table 2 for $M > 9$. A specific INC calculation, performed to fit our multiplicity data, gives a lower mean multiplicity (6.0 against our experimental value 6.67 ± 0.24 at 600 MeV/c) and no correlation between high multiplicities of charged particles in the final state and deep annihilations. However, the calculation was based on the INC model interpreted as a strict spallation model and low energy nucleons were neglected. On the basis of preliminary calculations the authors suggest that other fragmentation mechanisms, such as evaporation or percolation, should be considered. In these fragmentation models the number of emitted nucleons is very close to that of the excited ones, which in turn is correlated to the depth of the annihilation point.

As a last remark, we recall that Clover et al.[34] calculated the absorption probability (P_{abs}) in ^{12}C and ^{208}Pb vs. the nuclear radius for 590 MeV/c antiprotons; they used two values, 0 and 250 MeV, for the real $\bar{p}$ -nucleus potential. The P_{abs} maximum value occurs about at the nuclear matter half-density radius and the shape of the absorption probability distribution changes lightly as the nuclear radius increases. For this reason we assume that the absorption probability calculated for ^{12}C is valid for Ne too. It is drawn in fig.7 together with the Woods-Saxon distribution of the nuclear matter density $\rho(r)/\rho(0)$ for ^{20}Ne and a gaussian absorption probability distribution for $\bar{p}$ annihilating at rest on ^{20}Ne calculated by a formula given by Iljinov et al.[40]. The figure shows that, at 590 MeV/c, the $\bar{p}$ annihilation probability in the region $\rho(r) > 0.75 \rho(0)$ amounts to be within

10-20% over the total number of events. This figure is in very good agreement with the percentage of annihilation events with $M > 9$ reported in table 2.

4.5 K_S^0 production

As it concerns the K_S^0 production, our preliminary analysis does not reveal features different from those observed in the annihilation on free protons, where at 270 MeV a production rate of 3% was found and 70% of $K_S^0 \rightarrow \pi^+ \pi^-$ decays was observed in two charged prong annihilations [25,42]. We estimated for Ne a lower limit of $(2.2 \pm 0.4)\%$ for the production rate and observed 60% of $K_S^0 \rightarrow \pi^+ \pi^-$ decays in the annihilation channels with 5, 6 and 7 charged prongs.

5. Conclusions

The behaviour vs. energy and A of the $\bar{p}$ -nucleus reaction cross section is well reproduced by Glauber theory, which is due to the dominance of the annihilation channel over other processes.

The data concerning the charged particle multiplicities show that the interaction is dominated by surface annihilations on quasi free nucleons with a small, but not negligible, percentage of deep annihilations. The detection of deep annihilations is of interest because theoretical works predict that they might develop through mechanisms different from those included in the "standard physics" of the INC models, such as the annihilation on more than one nucleon [43,44] and the excitation of new degrees of freedom of the nuclear matter [45-47]. It is a common opinion that typical signatures of these exotic phenomena are an enhancement in hyperon and strange meson production and the emission of a high number of energetic nuclear fragments.

Our present data indicate that these phenomena occur with low probability and a high statistics is necessary to study

them. In fact at present we have not noticed any anomalous K_S^0 production. On the other side, there is a disagreement between our data and INC model predictions as regards the high multiplicity region in the charged particle multiplicity distributions. However at present is not clear whether this disagreement is due to exotic phenomena or to the inadequacy of the theories in dealing with multifragmentation, that is in drawing the number of the emitted nuclear fragments from the number of the excited nucleons.

From the experimental point of view, we plan to give further contributions by increasing the statistics and measuring the energy and the angular spectra of the pions and nuclear fragments. On the other side, new developments of the INC models and of the techniques for studying the $\bar{p}$ -interaction with few nucleon systems are needed.

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Table Captions

Table 1 - Nuclear fragmentation and charge exchange channels open below $E_{lab}=19.7$ MeV ($E_{c.m.}\approx 18.8$ MeV) for ^{20}Ne and ^{22}Ne nuclei.

Table 2 - σ_R = reaction cross section; $\bar{M}$ = mean number of charged prongs per event; $\langle n_{\pi^-} \rangle$ = mean number of π^- per event. These quantities are given for all the events, for events with $M \leq 9$ and $M > 9$. $P(M > 9) = \sigma_R(M > 9) / \sigma_R$ is the percentage of events with $M > 9$. The cross section values in brackets concern ^{20}Ne isotope.

Table 3 - Parameters utilized in the Glauber model described in the text.

Table 4 - Reaction cross sections vs multiplicity M .

Table 5 - Negative pion multiplicity distributions (%) at the three energies. The data concern only the recognized pions, not the pions effectively produced.

Figure captions

Fig. 1 - Comparison among reaction cross sections at different $\bar{p}$ momenta obtained with different experimental techniques. ($\diamond$) ref.[7]; (Δ) ref.[6]; (o) this experiment and ref.[1]; ($\bullet$) ref.[31]; ($\blacksquare$) ref.[32]; ^1H line from ref.[25]. The other lines are guides for the eye.

Fig. 2 - Reaction cross section data vs. the atomic number at 300 and 600 MeV/c. The data are from ref.[6](o), ref.[7]($\blacksquare$) and this experiment ($\bullet$).

The full and dashed lines are the result of the fit with Glauber theory at 600 and 300 MeV/c, respectively, having as a free parameter the ratio R of the $\bar{p}$ -neutron to $\bar{p}$ -proton total cross sections (see text). For comparison the curve obtained at 300 MeV/c with $R=1$ (dotted line) is also shown.

Fig. 3 - Comparison between the 300 MeV/c $\bar{p}^{12}\text{C}$ elastic scattering data of ref.[8] and the result of the Glauber theory obtained with the value $R=0.76$ (full line) coming from the fit of the reaction cross sections at the same energy (see fig.2). For comparison, the curve obtained with $R=1$ (dashed line) is also shown.

Fig. 4 - Comparison between the 600 MeV/c $\bar{p}^{12}\text{C}$ elastic scattering data of ref.[7] and the result of Glauber theory (full line) obtained with the value $R=0.94$ coming from the fit of the reaction cross section values at the same energy (see fig.2).

Fig. 5 - (a) Reaction cross sections at three $\bar{p}$ laboratory momenta vs. the charged prong multiplicity M .
(b) Percentage of events with a number of charged prongs $> M$ vs. M .

- (c) Mean number of stopped charged particles per event vs.M. Typical statistical errors are shown.
- (d) Mean number of negative pions per event vs.M. Typical statistical errors are shown.

Fig. 6 - Reaction cross section vs. multiplicity M. The full line represents a fit performed with a Maxwell distribution (see text).

Fig. 7 - Probability of $\bar{p}$ annihilation in Ne nuclei vs. the nuclear radius. The histograms were calculated by Clover et al.[34] for 590 MeV/c $\bar{p}$ on ^{12}C (the solid curve corresponds to a $\bar{p}$ -nucleus potential $V = 250$ MeV, the dotted curve corresponds to $V = 0$). The full line was calculated for $\bar{p}$ at rest following Iljinov et al.[40]. The nuclear matter density distribution for Ne is shown too (see text).

Table 1

Reactions	c.m. threshold energies (MeV)
$\bar{p} + {}^{20}_{10}\text{Ne} \rightarrow \bar{p} + {}^4_2\text{He} + {}^{16}_8\text{O}$	4.7
$\bar{p} + 2{}^4_2\text{He} + {}^{22}_6\text{C}$	11.9
$\bar{p} + {}^8_4\text{Be} + {}^{12}_6\text{C}$	12.0
$\bar{p} + p + {}^{19}_9\text{F}$	12.9
$\bar{p} + n + {}^{19}_{10}\text{Ne}$	16.9
$\bar{n} + {}^{20}_9\text{F}$	8.9
$\bar{n} + n + {}^{19}_9\text{F}$	15.5
$\bar{p} + {}^{22}_{10}\text{Ne} \rightarrow \bar{p} + {}^4_2\text{Ne} + {}^{18}_8\text{O}$	18.1
$\bar{p} + n + {}^{21}_{10}\text{Ne}$	10.4
$\bar{p} + 2{}^4_2\text{He} + {}^{14}_6\text{C}$	15.9
$\bar{p} + {}^8_4\text{Be} + {}^{14}_6\text{C}$	16.0
$\bar{p} + p + {}^{21}_9\text{F}$	15.5
$\bar{p} + n + {}^4_2\text{He} + {}^{17}_8\text{O}$	17.7
$\bar{n} + n + {}^{21}_9\text{F}$	18.1

Table 2

E (MeV)		19.6	48.7	179.6
All events	$\mathcal{G}_R(\text{mb})$	956 ± 47 (950 ± 47)	771 ± 28 (766 ± 28)	623 ± 21 (619 ± 21)
	$\bar{M}$	6.37 ± 0.33	6.43 ± 0.25	6.67 ± 0.24
	$\langle n_{\pi^-} \rangle$	1.13 ± 0.08	1.12 ± 0.08	1.20 ± 0.04
$M \leq 9$	$\mathcal{G}_R(\text{mb})$	843 ± 44	674 ± 26	532 ± 20
	$\bar{M}$	5.09 ± 0.28	5.09 ± 0.21	5.03 ± 0.20
	$\langle n_{\pi^-} \rangle$	1.06 ± 0.08	1.06 ± 0.08	1.11 ± 0.05
$M > 9$	$\mathcal{G}_R(\text{mb})$	113 ± 16	97 ± 10	95 ± 8
	$P(M > 9)$	11.9 ± 1.8	12.4 ± 1.3	15.2 ± 1.3
	$\bar{M}$	10.72 ± 0.18	10.66 ± 0.13	10.81 ± 0.14
	$\langle n_{\pi^-} \rangle$	1.75 ± 0.31	1.59 ± 0.30	1.74 ± 0.19

Table 3

p (MeV/c)	$\mathcal{G}_p$ (mb)	β_p^2 (GeV/c) ⁻²	$\mathcal{G}_p = \mathcal{G}_n$
300	225	32	-0.1
600	145	21	0.2

Table 4

M	19.6 MeV	48.7 MeV	179.6 MeV
0	0	3.1 ± 1.5	0
1	4.6 ± 3.1	6.9 ± 2.3	8.7 ± 2.5
2	45.9 ± 9.5	43.2 ± 2.3	34.3 ± 5.0
3	69.8 ± 12.4	53.2 ± 7.7	47.5 ± 5.6
4	123.3 ± 17.2	77.1 ± 8.5	57.9 ± 6.2
5	118.5 ± 16.2	114.1 ± 10.8	72.9 ± 7.5
6	164.4 ± 19.1	97.1 ± 10.0	71.0 ± 6.8
7	113.7 ± 16.2	100.2 ± 10.0	76.6 ± 7.5
8	113.7 ± 16.2	77.9 ± 8.5	77.2 ± 7.5
9	87.9 ± 14.3	97.1 ± 10.0	81.6 ± 7.5
10	58.3 ± 11.5	53.2 ± 6.9	41.7 ± 5.6
11	34.4 ± 8.6	29.3 ± 5.4	33.0 ± 4.5
12	16.2 ± 5.7	9.2 ± 3.1	14.3 ± 3.1
13	4.6 ± 3.1	3.1 ± 1.5	5.0 ± 1.9
14	0	1.0 ± 1.0	0.6 ± 0.6
15	0	1.0 ± 1.0	0
all events	956 ± 47	771 ± 28	623 ± 21

Table 5

n_{π^-}	19.6 MeV	48.7 MeV	179.6 MeV
0	20.8 $\pm$ 2.0	21.7 $\pm$ 2.3	18.7 $\pm$ 1.5
1	49.6 $\pm$ 3.4	49.5 $\pm$ 3.5	49.5 $\pm$ 2.4
2	25.2 $\pm$ 2.4	24.2 $\pm$ 2.5	25.6 $\pm$ 1.7
3	4.3 $\pm$ 1.0	4.1 $\pm$ 1.0	5.2 $\pm$ 1.0
4	0.2 $\pm$ 0.2	0.5 $\pm$ 0.3	0.9 $\pm$ 0.3

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7