сообщения
объединенного
института
ядерных
исследований
дубна

E1-90-486

Batusov Yu. A.

EXPERIMENTAL STUDY OF THE ANNIHILATION OF ANTIPROTONS AT REST IN NUCLEAR PHOTOEMULSION AND THE OPTICAL-CASCADE APPROACH

1990

Yu.A.Batusov, S.A.Bunyatov, I.V.Falomkin, N.I.Kostanashvili, G.B.Pontecorvo, A.M.Rozhdestvensky, M.G.Sapozhnikov, V.I.Tretyak
Joint Institute for Nuclear Research, Dubna

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

G.Bendiscioli, V.Filippini, A.Rotondi, P.Salvini, A.Venaglioni, A.Zenoni
Dipartimento di Fisica Nucleare e Teorica, University of Pavia, and INFN - Sezione di Pavia, Pavia, Italy

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

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

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

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

A.S.Iljinov, E.S.Golubeva
Institute for Nuclear Research, Moscow, USSR

1. INTRODUCTION

A feasible method of studying the interaction of antimatter with matter consists in the investigation of nuclear reactions occurring when slow antiprotons collide with atomic nuclei. The most revealing reactions may turn out to be the annihilations in a nucleus of antiprotons at rest, since in this case the reaction energy (1877 MeV) is known exactly, as is the scenario of antiproton capture, absorption and annihilation processes, occurring in a substance, it being based on available experimental data on $\bar{p}$N-collisions[1] and on various theoretical calculations within the framework of cascade models that describe quite well the main characteristics of $\bar{p}$-nucleus interactions[2].

The most prominent feature of such processes is annihilation of the antiproton, mainly at the periphery of the nucleus, which proceeds on a single or several nucleons resulting in 95% of the interactions producing an average of 5 π-mesons of <230> MeV kinetic energy; part of the pions leave the nucleus, while the remainder induces in the nucleus a cascade of successive πN- and NN-collisions.

For obtaining a detailed picture reflecting the mechanisms of antiproton interaction with various nuclei it is necessary, on the one hand, to accumulate systematically experimental data concerning the production in such interaction of all possible charged and neutral particles and their correlations and, on the other hand, to improve the theoretical models of antiproton annihilation processes occurring in nuclei. In this work recent results obtained in the PS-179 CERN experiment, in which charged particle production was studied in the absorption of antiprotons in nuclear photoemulsion[3], are presented, and comparison is performed of the obtained experimental results with calculations carried out in the optical-cascade model representing a development of the multipion-nuclear interaction model for $\bar{p}$-nucleus annihilation[4].

2. THE EXPERIMENTAL TECHNIQUE AND RESULTS

Technical issues related to the preparation and exposure of photoemulsion chambers at the LEAR facility of CERN are dealt with in detail in ref.[3]. In the present work scanning and measurement of absorption events of antiprotons by nuclei in the photoemulsion were performed, as before, in the developed layers using a microscope with a general magnification factor of 1350X, but the scanning procedure was altered, however: antiproton stopping points were recorded by along-the-track scanning of the beam particles. Such a scanning procedure completely eliminated losses both of events with low charged particle multiplicities and of zero-prong stops, which is especially important. A total of 3453 stopping antiprotons were recorded.

In each event ("star") the secondary charged particles were identified by their relative ionization losses. Singly charged shower particles with a relative ionization lower than 1.4 ($\beta\gamma = \frac{p}{m} > 1$, here p and m are the particle momentum and mass, respectively) were classified as "s"-particles; in the main, these were secondary pions with an insignificant contribution of fast protons. Singly and doubly charged grey particle tracks with a relative ionization higher than, or equal to, 1.4 ($0.23 < \frac{p}{m} \leq 1$) were termed "g"-particle tracks - such were charged particle tracks ranging more than 3000 μm in the pho-

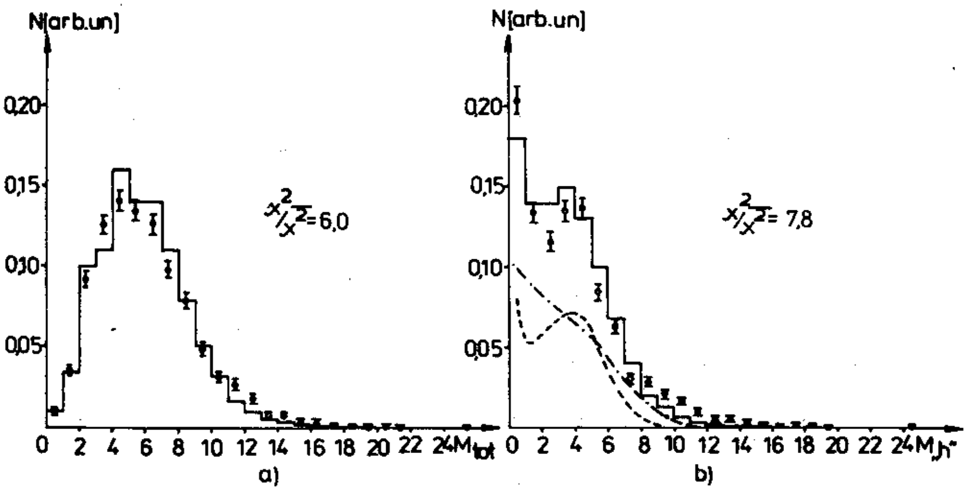

Fig.1. Multiplicity distribution for particles produced by antiprotons stopping in the photoemulsion: a) secondary charged particles, b) h-particles. The points are experimental, the histogram is calculated by the optical-cascade model, the dashed line is the contribution of the nucleus $\langle ^{14}N \rangle$, and the dash-dotted line represents $\langle ^{93}Nb \rangle$.

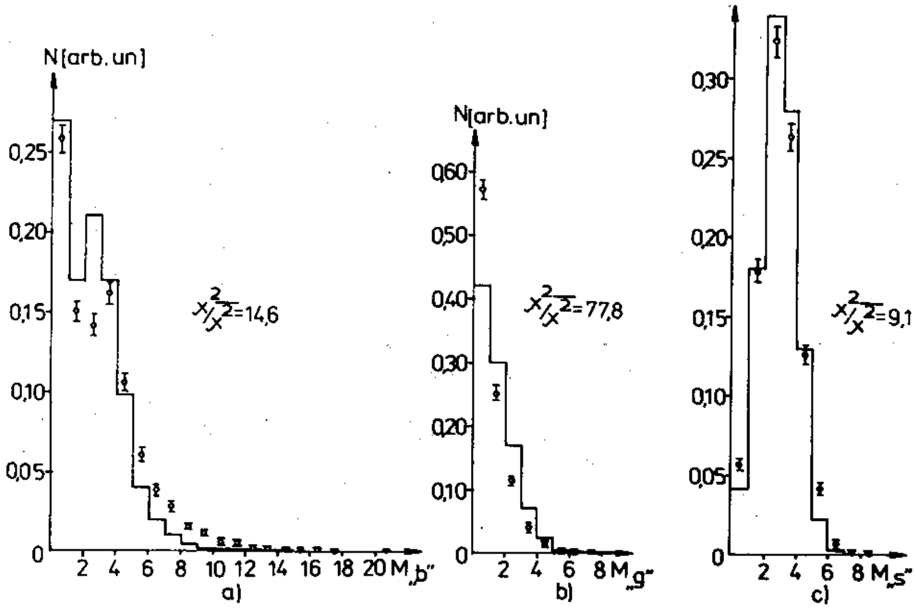

Fig.2. Multiplicity distribution for particles produced by antiprotons stopping in the photoemulsion: a) b-particles, b) g-particles, c) s-particles. The points are experimental, the histogram is calculated by the OCM.

toemulsion. Black tracks shorter than 3000 μm produced by nuclear fragments or slow protons were termed "b"-particles. Slow protons and nuclei knocked out from nuclei or emitted at the evaporation stage and in the multifragmentation process give rise in photoemulsion experiments to the so-called strongly ionizing "h"-particles. We note that in a multi-prong star a track is classified as prong, if it exhibits a definite direction and is not shorter than 2 μm, while in one-prong events the track is required to have a range not shorter than 10 μm. The relative angles of the outgoing tracks were measured for all secondary charged particles in each event, and ranges were measured for particles stopping within a single photoemulsion layer.

In figs.1 and 2 the secondary charged particle multiplicity distributions are presented for all registered antiprotons stopping in the photoemulsion. The average number of charged particles was (5.65±0.10). The relative number of 0-prong events was (1.0±0.2)%. Possible sources of such events are either annihilation of an antiproton on a nucleus, and subsequent absorption by the nucleus of all the produced charged pions, together with possible emission of the remaining neutral pions without any apparent disintegration of the nucleus which, owing to the large energy release in annihilation, is not highly probable, or the stopping and annihilation of an antiproton on the hydrogen present in the photoemulsion and subsequent production of solely neutral mesons. In performing theoretical calculations of annihilation processes of $\bar{p}$ on nuclei present in the photoemulsion, the above fact requires one to take into account annihilation on hydrogen, as well as annihilation on average light (14 nucleons) and average heavy (93 nucleons) nuclei (^{14}N and ^{93}Nb, respectively).

The multiplicity distributions of "b", "g", "s" and "h" particles are given in Figs.1 and 2. The distribution of "h" particles is characterized by the existence of two maxima, one at $M_h = 0$ and the other in the region of $M_h = 3$-4. It must be pointed out that distributions of a similar shape were observed for "h" particles by C.J.Waddington[5] in a study of the interaction of primary cosmic-ray nuclei with an energy

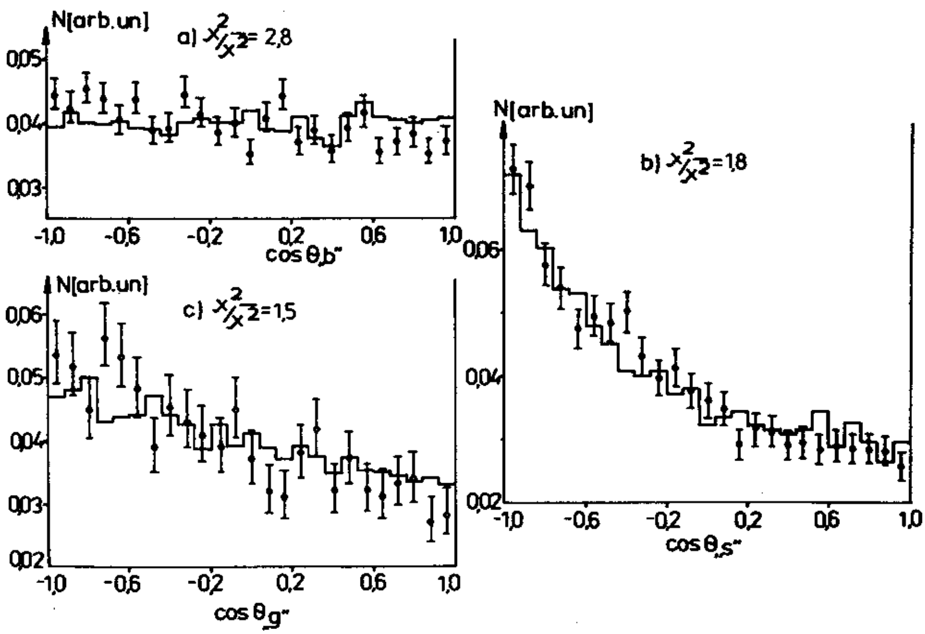

Fig.3. Angular distribution of secondary charged particles produced by antiprotons stopping in the photoemulsion: a) for b-particles, b) for s-particles, c) for g-particles. The points are experimental, the histogram is calculated by the OCM.

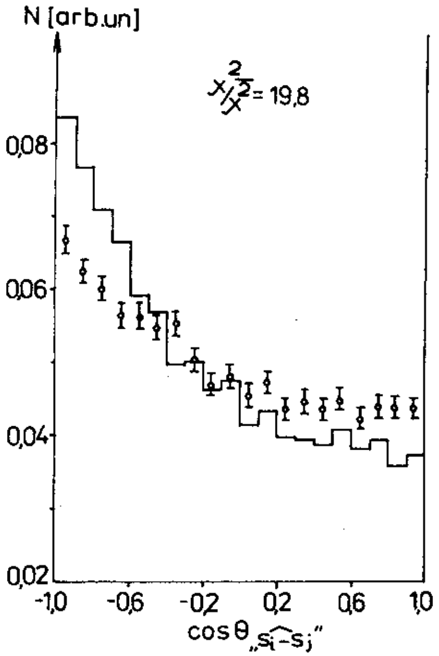

Fig.4. Dependence of angular correlations for s-particles produced by antiprotons on nuclei in photoemulsion. The points are experimental, the histogram is calculated by the OCM.

of 4.5 GeV/nucleon with the nuclei in a photoemulsion. The authors of ref. /6/ attribute the appearance of the second maximum to a more complete (as compared with protons) disintegration of the light nuclei (C, N, O) in the photoemulsion by the primary relativistic nuclei. The resemblance between the shapes of the distributions for "h" particles in these two processes points to extremely similar mechanisms of the intranuclear cascade development in the case of antiproton annihilation and in the case of relativistic nucleus-nucleus interaction in photoemulsion, as well as to the significant contribution of annihilation on the light nuclei in photoemulsion.

In Fig.3 the angular distributions for secondary charged particles are presented. Since the direction in which the stopped antiproton travelled is lost, the angles here are measured clockwise with respect to the first "s" particle track after the antiproton along the direction of flight. It can be seen that the distributions for the "b" and "g" particles are close to isotopic, while the angular distribution for "s" particles displays a preference for 180^0 opening angles between the outgoing particle tracks. The distribution over angular correlations of "s" particles (Fig.4) exhibits a similar shape. These experimental data indicate a possible noticeable production probability in the annihilation of antiprotons at rest on nuclei in photoemulsion of heavy mesons (η, ρ, ω, A,...) decaying into pions /4/.

3. OPTICAL-CASCADE MODEL (OCM) OF ANTIPROTON ABSORPTION AT REST BY NUCLEI

Within the framework of the OCM the absorption of a stopping antiproton is considered as a multistage process /4/.

Here the initial stages of the process, namely, the production and de-excitation of a $\bar{p}$-atom, as well as the capture of an antiproton by a nucleus from a level of the hadronic atom, is described with the aid of the optical model. The primary annihilation of the antiproton on the nucleons in the nucleus, which involves a significant transfer of energy to several pions, serves as a natural boundary between the initial and final stages of the reaction. The subsequent stages in which the energy released in the primary absorption act is dissipated and de-excitation of the residual nucleus are described, respectively, by the intranuclear cascade model and by statistical evaporation or multifragmentation models (depending on the excitation energy of the residual nucleus). Thus the optical-cascade approach essentially consists in the initial conditions for the kinetic equation describing the deep-inelastic process initiated by several fast pions being defined within the framework of the optical model.

The computed radial dependence of the antiproton absorption probability of the antiproton from a state of the hadronic atom at the periphery of the nucleus is approximated by a Gaussian

$$P_{abc}(r) \simeq \exp\{-(r - R_{med})^2/2\sigma_a^2\}$$

with the following parameters: $R_{med} = R_{1/2} + t/2$, $R_{1/2}$ is the radius corresponding to half density, $t = 2.3$ fm is the thickness of the diffuse layer, $\sigma_a = 1$fm is the dispersion.

The mechanism of absorption and annihilation of an antiproton at rest is described in greater detail in ref.[4]. The incoherent multipion-nucleus interaction initiated by the antiproton annihilation products is considered within the framework of the intranuclear cascade model. Owing to a significant amount of pions being produced in antiproton-nucleon annihilation and to a large number of particles participating in the intranuclear cascade, the said computation is based on the version of the intranuclear cascade that takes into account the local decrease of nuclear density occurring during the development of the cascade (the so-called "trawling" effect)[7,8]. Unlike the versions presented in previous publications[8], this one also provides a more correct description of the cascade development in time. It must be pointed out that, as shown in ref.[8], the decrease of nuclear density influences significantly certain characteristics of the antiproton-nucleus interaction, especially those related to the production of protons.

The nucleus is considered to consist of individual nucleons the centres of which are distributed in accordance with the distribution of nuclear density $\rho(r)$. A cascade particle may interact with a partner the centre of which is inside a cylinder of radius $r_{int} + \lambda$, and the axis of which is directed along the velocity $\overline{v}_i$ of the incident particle. Here $r_{int} \simeq 1.3$ fm, which is close to the range of strong interaction, λ is the wavelength of the cascade particle. Unlike the version presented in ref.[8], where, in the Monte Carlo simulation of the intranuclear cascade, of all the cascade particles only the fastest was the one to be followed first, the present version involves a time coordinate t introduced explicitly for the development of the process. At a certain moment t_0 the time Δt required for reaching its nearest partner is calculated for each cascade particle. Then, the smallest of these times τ is chosen corresponding to the number i of the particle which may interact with the intranuclear nucleon before any other cascade particle. τ is the time quantum after which the whole set of cascade particles having travelled a distance $\overline{l}_i = \tau \times \overline{v}_i$ is further considered. At the moment of time $t = t_0 + \tau$ the probability is considered for the i-th particle to interact with a target nucleon. And so on until all the cascade particles leave the nucleus.

After the antiproton has been absorbed by the nucleus and the fast stage of the multipion-nucleus interaction has been completed, there remains a highly excited residual nucleus. If the excitation energy is close to the total binding energy of the nucleons in the nucleus, $E^* \leq 5$ MeV/nucleon, then the explosive mechanism prevails in the disintegration. In the case of light nuclei ($A \leqq 16$) the Fermi model of explosion decay[9] is used for describing the decay, while in the case of medium-heavy nuclei the statistical model of multifragmentation[9] is applied.

Photoemulsion includes the following components: hydrogen, light (C, N, O) and heavy (Ag, Br) nuclei. Therefore, to calculate the general characteristics of antiproton annihilation on nuclei in photoemulsion within the framework of OCM one must know the contribution to the process being studied of each component. The upper limit of the contribution of $\overline{p}$ annihilation on hydrogen was estimated from the number of stars recorded with 0 prongs and with even numbers of s-prongs without any sign of a recoil nucleus and an electron. It turned out to be $(6.0 \pm 0.4)\%$. The distribution of $\overline{p}$ stops on the light and on the heavy components in the photoemulsion is not known exactly. It is natural to assume two possibilities: the probability of capture by the atom is proportional to the concentration n of nuclei of the given element or, on the other hand, it is proportional to n x Z, where Z is the charge of the nucleus. From ref.[10] it follows that the total number of pion (π^-) stops on light nuclei in photoemulsion, computed for these two assumptions, equals 38%. Assuming the distributions of $\bar{p}$ and of negative pion stops in the photoemulsion to be similar we took for calculations the contribution of $\bar{p}$ interactions on the heavy component to be 56%.

4. COMPARISON OF THE CALCULATIONS WITH EXPERIMENTAL RESULTS

The results of calculations of the interaction of antiprotons stopping in photoemulsion within the framework of the OCM are presented in the Table and in Figs.1 to 6. Comparison of the average multiplicities of various types of secondary charged particles recorded in the photoemulsion with computed values (see the Table) reveals that these data differ little and correctly reflect the general tendency exhibited by correlations between different kinds of charged particles. This fact indicated that, most likely, the correct ratio between the components present in the photoemulsion was chosen for the process under consideration. The multiplicity distributions for all the charged particles, as well as for the s-, b- and h-particles, but with the exception of the distribution for g-particles (Figs.1,2) agree quite satisfactorily in shape with the computed distributions (the $\chi^2/\overline{\chi^2}$) values are given in the figures). A good agreement is also observed for the angular distributions of all types of particles (Fig.3), as well as for the correlation dependences of the total multiplicity of secondary charged particles upon the average values for s- and h-particles (Fig.5) and for the correlation of the mean number of s-particles upon the number of h-particles in a given event (Fig.6).

At the same time quite a strong discrepancy is observed between the experimental data and the results of calculations for multiplicity distributions for the b- and h-particles in the region of small M_b and M_h values (0÷2), although the shape of multiplicity distributions for h- and b-particles calculated for the light nuclei (H, C, N, O) in photoemulsion correctly displays the form of the spectrum with two maxima (Figs.1, 2). In the same region of dependence of correlations of secondary s-particles upon the mean values for h-particles a noticeable difference can be seen between theoretical and experimental results (Fig.6).

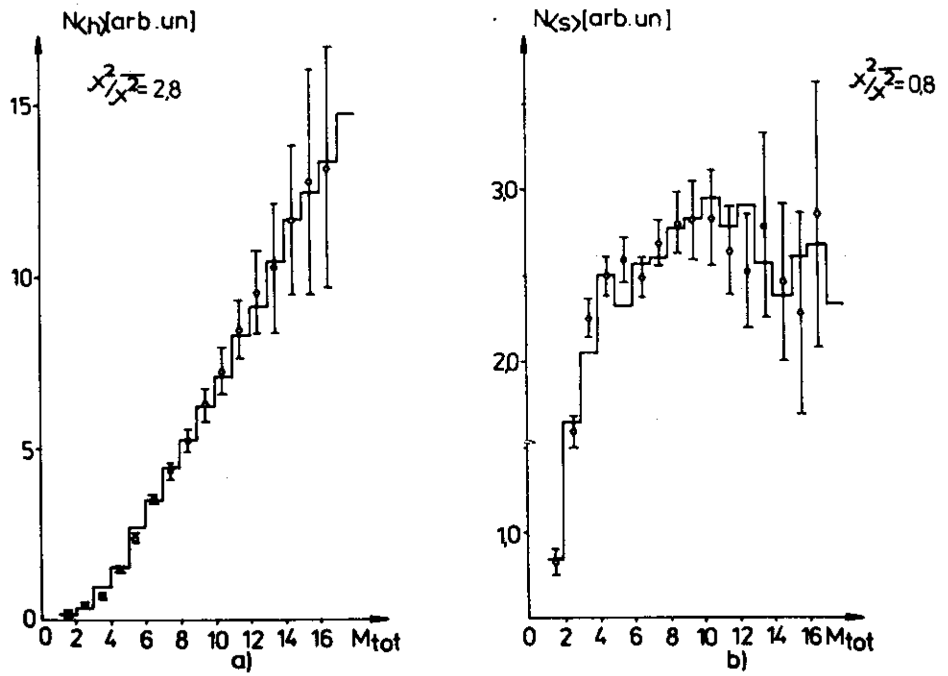

Fig.5. Correlation dependences of secondary charged particle multiplicities upon: a) the average number of h-particles, b) the average number of s-particles. The points are experimental, the histogram is calculated by the OCM.

And, finally, the distributions of all possible angular correlations for the s-particles obtained experimentally (Fig.4), while correctly reflecting the general tendency, differ strongly form the calculated quantities in the region of 180°. This seems to indicate the contribution to the mechanism of antiproton absorption by nuclei in the photoemulsion of certain

Table

The types of particle	The average number of charged particles				
	< Mtot >	< Mh >	< Ms >	< Mb >	< Mg >
Experiment	5.65±0.10	3.29±0.06	2.39±0.04	2.58±0.04	0.68±0.01
OCM calculation	5.41	3.05	2.37	1.99	1.06

processes not taken into account, such as the production in the annihilation of heavy mesons (η, ρ, ω, A, ...) or of more exotic bound states, for instance, involving the production of quark-gluon plasma.

Thus, the performed experimental investigation of charged particle production in the absorption of slow antiprotons in photoemulsion and comparison of the experimental results with theoretical calculations within the framework of the optical-cascade model taking into account the trawling effect and a more correct description of the development of the cascade in time shows quite a good agreement between the general characte-

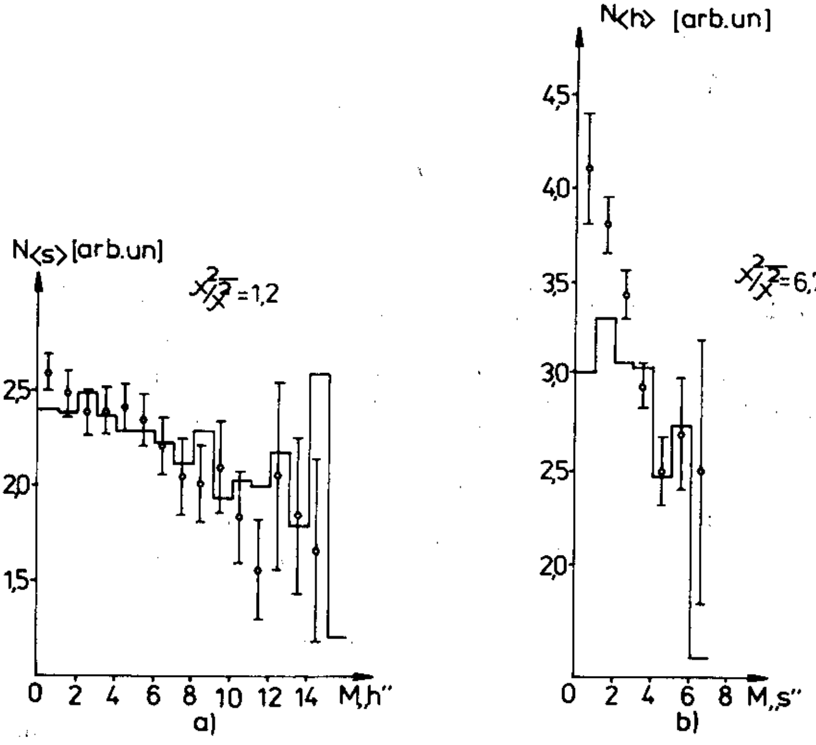

Fig.6.a) Correlation dependences of h-particle multiplicities upon the average number of s-particles, b) correlation dependences of s-particle multiplicities upon the average number of h-particles.

ristics of this process and the assumptions concerning the mechanism of capture, absorption and annihilation of antiprotons by nuclei taken into account in the computation model. At the same time, for obtaining a more detailed accordance between calculations and experimental data further enhancement of the experimental information is needed, as well as introduction into the computation of more subtle interaction effects of antiprotons with nuclei.

REFERENCES

1. Flaminio V. et al.-CERN-HERA, 84-01, Geneva, 1984.
2. See, for example, J.Cugnon et al.-Nucl.Phys., A-500 (1989), 701 and references therein.
3. Balestra F. et al. - Euro Phys. Lett., 1986, 2, p.115.
4. Iljinov A.S. et al. - Nucl. Phys., 1982, A382, 83, p.378.
5. Waddington C.J. - Nucl. Phys., 1964, 31, p.748.
6. Powell C.F. et al. - The study of elementary particles by the photografic method, Pergamon press, 1959.
7. Barashenkov V.S. et al. - Yad.Fis., 1971, 13, p.743.
8. Golubeva Ie.S. et al. - Nucl. Phys., 1989, A483, p.539.
9. Botvina A.S. et al. - Nucl. Phys., 1987, A475, p.663.
10. Batusov Yu.A. et al. - Yad.Fis., 1967, p.1151.

Received by Publishing Department
on October 25, 1990.