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NEW TRENDS IN THE INVESTIGATION OF ANTIPROTON-NUCLEUS ANNIHILATION

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1. INTRODUCTION

Experiments at LEAR have provided valuable information on the antiproton-nucleus interaction at low energies, T < 200 MeV (see, reviews [1,2]). Such gross features of the $\bar{p}A$ interaction as the energy dependence of cross sections, multiplicity distributions of annihilation mesons, angular and momentum spectra of outgoing particles etc. are known now. This information provides a reference frame for future tasks to be carried out at high intensity hadron facilities such as the KAON factory or SUPERLEAR-type machines. In high energy antiproton-nucleus physics one can single out at least two types of problems . The first involves investigation of the mechanisms of antiproton interaction with nuclei. In a certain sense it represents a repetition of the program performed with protons and pions. Such experiments are needed for a better understanding of which phenomena are to be regarded as conventional.

Problems of the second type include the investigation of specific antiproton-nucleus annihilation phenomena. How does a nucleus react to a near 2 GeV energy release occurring in a small volume on the surface or inside the nucleus? How strong is the final state interaction of annihilation mesons? Is annihilation on few-nucleon clusters possible? Does the annihilation probability on a bound nucleon differ from the annihilation probability on a free nucleon? All these problems represent examples of "pure" antiproton physics. We believe it is these aspects of antiproton-nucleus physics that will become more and more important in the future. In this article we try to persuade the reader that one of the most promising paths in the studies of antiproton interactions with nuclei at high energies is the investigation of effects of final state interactions (FSI) of annihilation mesons with nucleons of the residual nucleus.

Indeed, antiproton annihilation in a nucleus actually provides a "beam" of secondary mesons just on the surface or inside the nucleus. A remarkable feature of annihilation is the rich variety of annihilation mesons and possible reaction channels. Thus, for antiproton annihilation at rest approximately 150 different annihilation channels have been measured. It was found that the ρ-meson is produced in 32%, the ω-meson in 11%, the $a_2(1320)$-meson in 8% and the η-meson in 7% of all annihilations. It is quite natural to try to use antiproton-nucleus annihilation for studying effects of heavy meson interactions with nucleons. The study of such interactions is at the very beginning.

Approximately from 5 to 6% of all the annihilations of stopping antiprotons result in the production of $K\bar{K}$-pairs. The yield of strange mesons increases with energy and may reach up to 10-20% in the region of few GeV. Antiproton-nucleus annihilation with strange particle production provides a good signature for studying various nontrivial effects (see Ch.3). It opens a new possibility for hypernuclear physics owing to the unexpectedly high yield of hypernuclei of heavy elements ($\approx 10^{-4} - 10^{-3}$ per annihilation), discovered in the PS 177 experiment at LEAR [3,4].

Annihilation of antiprotons with an energy of $\approx$ 3-4 GeV may result in the production of different charmonium states. This opens up entirely new prospects for the spectroscopy of charmonium since, while in e^+e^- - annihilation only states of a fixed quantum number $J^{PC} = 1^{--}$ can be produced, in $\bar{p}p$-annihilation no such restrictions exist and various charmonium states may be formed directly [5,6]. Rescattering of the charmonium states produced in $\bar{p}p$-annihilation in the nucleus may be used for searching for some nontrivial effects, for instance, to look for supernuclei - nuclei with a bound charmed baryon [7].

The material is organized as follows. In Chapter 2 a short summary of our present experimental knowledge of rescattering processes in $\bar{p}A$ -annihilation is given. Chapter 3 contains a discussion of strange particle production in $\bar{p}A$-annihilation. Problems in studies of heavy mesons and charmonia rescattering are presented in Chapter 4. The concluding Chapter 5 is somewhat unusual for $\bar{p}A$ physics at intermediate energies: in it the *link is considered between* the characteristics of FSI in $\bar{p}A$ annihilation and astrophysics.

2. FINAL STATE INTERACTION OF ANNIHILATION MESONS

The large cross section of the elementary $N\bar{N}$ interaction prevents intermediate energy antiprotons from penetrating deep into the inner region of a nucleus. Annihilation of antiprotons takes place mainly on the surface of a nucleus where a "beam" of mesons is created. In spite of isotropic angular distributions in the center of mass of the $N\bar{N}$ system, this "beam" of mesons produced in antiproton annihilation in flight is collimated, owing to simple kinematical reasons, in the forward direction. For instance, at 6 GeV/c all the π-mesons are within a 20^0 cone in the forward hemisphere [8]. The mean pion multiplicity in $\bar{p}p$ annihilation is large and amounts to $n_\pi = 5.01 \pm 0.23$ [9] even for stopping $\bar{p}$, the energy spectrum of annihilation π-mesons has a maximum at $T \approx$ 200 MeV, i.e. in the region of the Δ_{33}-resonance excitation. Both these reasons lead to an enhancement of the FSI of mesons with nucleons of the residual nucleus. In this connection there is some hope that the energy of annihilation may be confined to a small volume inside the nucleus and that the energy density in $\bar{p}A$ annihilation may reach the values of *1-2 GeV/fm^3 where various nontrivial effects such as the* formation of quark-gluon plasma (QGP) drops may be expected.

However, the searches for apparent signatures of QGP in $\bar{p}A$ annihilation have led to discouraging results. It has been shown [10] that the K^+/π^- ratio is practically independent of A and equals *2.3, 2.8, 3.0* and *3.0 % for 500 MeV/c $\bar{p}$* annihilation in hydrogen, deuterium, carbon and uranium, respectively.

Cascade model calculations [11-15] show that in the case of $\bar{p}$ annihilation in heavy nuclei the fraction of pions interacting with nucleons of the residual nucleus is not too large and amounts to 40 -50 %. Approximately one half of the annihilation energy is transferred to the nucleus due to the absorption of pions, another part is dissipated in the reactions of quasielastic scattering [12]. It must be stressed that "thermalization" of the whole nucleus does not take place [16], the annihilation energy is taken away by pions and few nucleons escaping from the nucleus. The mean number of interactions undergone in the nucleus by a nucleon ejected upon annihilation is only 1.4-1.5 for 300 MeV/c antiproton annihilation on a nucleus with A=100 [16].

This picture of "soft" $\bar{p}A$ annihilation provides an explanation of why the multiplicity distributions of charged pions on a bound and on a free nucleon are very similar. Corresponding data are shown in the Table 1, where the multiplicity distribution of π^- from annihilation of antiprotons stopping in hydrogen is compared with those for $\bar{p}p$ annihilation on a proton bound in ^{4}He [17,18].

Table 1. Multiplicity distributions of negative mesons in $\bar{p}p$ annihilation at rest on a free proton and on a proton bound in ^{4}He. The prediction of a statistical annihilation model [19] is given in the fourth column.

$N(\pi^-)$	$\bar{p}p$ (free) [9] %	$\bar{p}p$ (bound in ^{4}He) [17,18] %	theory [19] %
0	$4.1^{+0.2}_{-0.6}$	4.97 ± 0.5	2.37
1	43.1 ± 0.9	46.71 ± 1.64	45.5
2	47.3 ± 1.2	43.90 ± 2.53	44.9
3	4.25± 0.31	4.2 ± 1.42	4.89

One can see that the difference between the multiplicity distributions from annihilation on free and on bound nucleons reaches few percent, at most. It implies that the rescattering of annihilation mesons does not alter drastically the global features of the reaction.

Nevertheless, the FSI of annihilation mesons are by no means negligible and may initiate some interesting effects. For example, in the case of $\bar{p}^4$He annihilation FSI reduces the probability of a three-nucleon system to be formed in a bound state. In a sense, one may regard the probability for a 3N system to survive in a bound state after annihilation as an estimate of the magnitude of FSI effects. For this purpose it is useful to introduce the quantity

$$P_{FSI} = 1 - \frac{\sigma_{3N}}{\sigma_{ann}} \qquad (2.1)$$

where σ_{3N} is the cross section of $\bar{p}^4$He annihilation with the formation of ^{3}He and ^{3}H.

In Fig.1 the energy dependence of P_{FSI} is shown. One can see that FSI effects are around 35 % for $\bar{p}^4$He annihilation at rest and increase with the antiproton energy. At 600 MeV/c practically one half of all the annihilations results in destruction of the ^{4}He, mainly due to FSI.

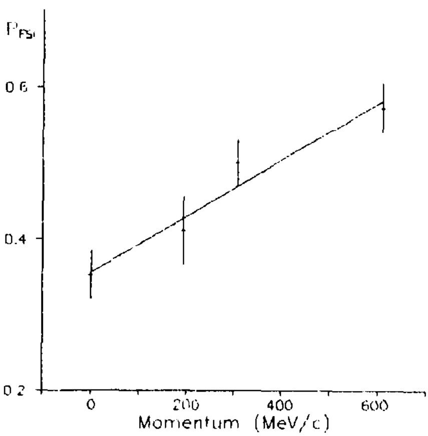

Fig.1. Energy dependence of the probability P_{FSI} (2.1) for the 3N system to survive in a bound state after $\bar{p}^4$He annihilation (in percent). The data are from [18]. Full line was drawn only for convenience of a reader.

A direct consequence of FSI is the decrease of the mean pion multiplicity in $\bar{p}A$ -annihilation. In Table 2 the mean π^- multiplicities in $\bar{p}A$ annihilation on different light nuclei are given as well as their ratio R^- to the mean multiplicity for $\bar{p}d$ annihilation.

Table 2. Mean π^- multiplicities $\langle n^- \rangle$ for $\bar{p}A$ annihilation at 600 MeV/c and their ratios R^- to the mean multiplicity for $\bar{p}d$ annihilation. $R^- = \langle n^- \rangle_A / \langle n^- \rangle_D$ (data from [20,21])

A	$\langle n^- \rangle$	R^-
D	1.73 ± 0.04	1.
^3He	1.61 ± 0.03	0.93 ± 0.03
^4He	1.66 ± 0.03	0.96 ± 0.03
^{12}C	1.58 ± 0.07	0.91 ± 0.05
^{20}Ne	1.37 ± 0.04	0.79 ± 0.03

One can see that even for light nuclei the average π^- multiplicity decreases by 4-20 % as compared with deuterium. This may be due to charge exchange reactions, such as $\pi^- + N \longrightarrow \pi^0 + X$, and also to the absorption of annihilation mesons, such as $\pi^- + NN \longrightarrow N + N$. The disappearance of π^- in CEX reactions is strongly compensated by their production in the reverse processes of π^0 charge exchange (like $\pi^0 n \longrightarrow \pi^- p$). That is why one may assume that $\langle n^- \rangle$ decreases mainly owing to absorption of the pions. However, direct searches for absorption of annihilation pions were unsuccessful [23]. The ASTERIX collaboration [23] has studied the stopped antiproton annihilation in ^{14}N and has not seen the back-to-back high energy protons (which should be produced in the $\pi + NN \longrightarrow N + N$ reactions) at the level of 0.3% of all annihilations. They argue that the decrease of the mean pion multiplicity $\langle n^- \rangle$ in $\bar{p}A$ annihilation is mainly due to CEX reactions.

New information on the magnitude of FSI effects in $\bar{p}$

annihilation on the lightest nuclei were obtained in recent measurements of the PS 179 experiment at LEAR. The $\bar{p}^3He$ annihilation at rest was studied, and events with different numbers of protons in the final state were selected. It turned out that in 3.75 % of annihilations no protons or deuterons were recorded in the final state. Such events should be due to two-step processes, when annihilation on a proton in ^3He is followed by CEX ($\pi^- + p \longrightarrow \pi^0 + n$, $\pi^0 + p \longrightarrow \pi^+ + n$) or pion absorption ($\pi^- + d \longrightarrow n + n$). Assuming the probability of latter processes to be smaller than the former, one may estimate that the CEX of all pions on both nucleons in ^3He may occur in 11% of all $\bar{p}^3He$ annihilations.

It is interesting to look for FSI effects in the momentum distributions of different particles involved in $\bar{p}A$ annihilation. We shall start our consideration from the momentum distribution of annihilation pions. It is well known [19] that the momentum distribution of pions from free $\bar{p}p$ annihilation does not exhibit a simple Boltzman-like behaviour.

$$\frac{dN}{dp} = \frac{p^2}{E} \exp(-E/T) \qquad (2.2)$$

where E is the total pion energy.

There is a depletion of pions with low momenta in comparison with the distribution (2.2). This is why the pion momentum distribution from $\bar{p}p$ annihilation is usually fitted with a Boltzman formula multiplied by p^2/E^2 for suppressing the low momentum part of the spectrum [19]:

$$\frac{dN}{dp} = \frac{p^4}{E^3} \exp(-E/T). \qquad (2.3)$$

Expression (2.3) also works well for the pion momentum spectrum in $\bar{p}d$ annihilation [22]. However, the situation changes even in the case of $\bar{p}$ annihilation in the lightest nuclei.

In Fig.2 the momentum distribution of pions from $\bar{p}^4He$ annihilation at rest is shown. The dashed line corresponds to the modified Boltzman distribution (2.3) with the parameter T=125 MeV obtained in the case of $\bar{p}d$ annihilation at rest

[22]. One can see that, instead of a depletion, an excess of pions with low momenta is observed. This is a natural consequence of the rescattering of pions in the final state. In general, pion momentum distributions from annihilation on nuclei are described much better by the normal Boltzman distribution (2.2) (solid line in Fig.2).

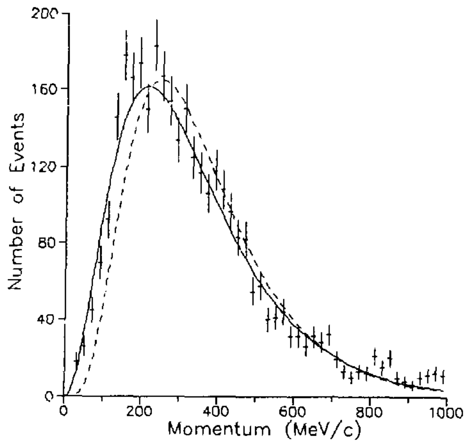

Fig.2 The momentum distribution of π^- from $\bar{p}^4He$ annihilation at rest [18]. The dashed line corresponds to the modified Boltzman distribution (2.3) with T=125 MeV obtained for $\bar{p}d$ annihilation at rest [22]. The solid line corresponds to a normal Boltzman distribution (2.2) with T=136 MeV.

Rescattering of annihilation mesons also distorts the momentum spectrum of protons escaping from the nucleus after annihilation. In Fig.3 one can see the momentum distribution of spectator protons obtained by the ASTERIX group [23] from studies of antiproton annihilation at rest in deuterium.

A peculiar feature of the spectrum is a prononuced plateau between 200 and 400 MeV/c. Such behaviour is in sharp contrast with the normal proton-spectator distribution shown by the dashed line in Fig.3. It is tempting to attribute this plateau to FSI effects of annihilation mesons. However, calculation of the spectrum [24] where rescattering of a part of the annihilation mesons is taken into account (solid line) fails to explain the experimental data.

This failure should be kept in mind in connection with another long-known paradox of unusual proton momentum

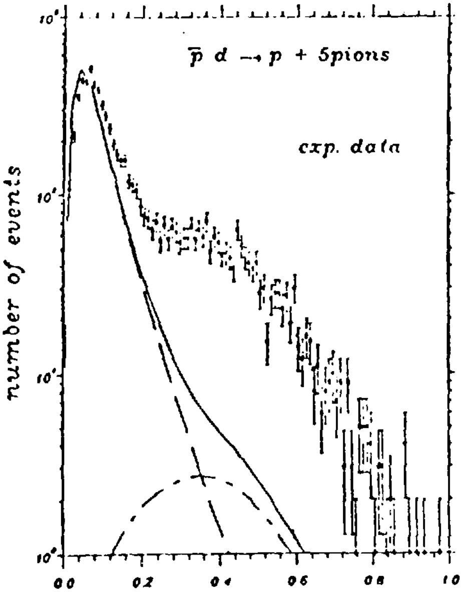

Fig.3 The momentum distribution of proton -spectators in stopped antiproton annihilation in deuterium [23]. The usual proton -spectator distribution is shown by the dashed line. The solid line is the overall result of calculation [24] with the rescattering of pions taken into account. The dot-dashed line is the sole contribution of the rescattering of pions.

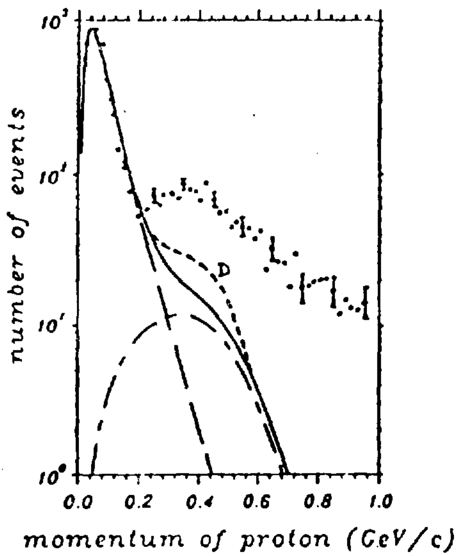

Fig.4 The momentum distribution of proton - spectators for $\bar{p}d \longrightarrow pK\bar{K}n\pi$ annihilation [25]. The curves correspond to the calculation from [24]. The long-dashed line is the usual proton - spectator distribution, the dash-dotted line is from π - rescattering. The solid line is their coherent sum. The curve marked D shows the deuteron D-state contribution.

distribution in $\bar{p}d$ annihilation into $K\bar{K}\pi$ channels. This anomaly was discovered in 1973 [25] when the proton momentum spectrum in reaction $\bar{p} + d \longrightarrow p_S + K\bar{K} + N\pi$ was also found to deviate strongly from the pure spectator distribution (see, Fig.4).

One can see in Fig.4 the same shoulder as in Fig.3 and also the same failure of theory [24]. It occurs that neither the inclusion of π and K rescattering (solid line) nor taking into account the D-state contribution (dashed line) can reproduce the data. This discrepancy stimulates certain speculations that one may be observing the effects of a quark-gluon plasma in $\bar{p}A$ annihilation [26]. But before drawing any definite conclusion it must be stressed that the experimental data from Fig.4 were not remeasured since 1973 and the question about the magnitude of the aforementioned difference is still open. Moreover, not all meson rescattering contributions were taken into consideration in [24].

Problems with the explanation of proton momentum distributions also exist in the case of $\bar{p}$ annihilation on heavy nuclei. For instance, standard cascade model calculations [16] of proton spectra in $\bar{p}\,^{12}C$ annihilation also yield smaller values than the experimental ones for the high-momentum part of the spectrum. To explain this "hard" contribution it was speculated [27] to be due to the absorption of few off-shell pions on one nucleon of the nucleus. However, description of the high-momentum part of the spectrum has always represented a difficult problem, not only in $\bar{p}A$, but also in πA and pA interactions. To prove unambiguously that the observed distortions are indeed inexplicable within the framework of conventional approaches is very doubtful.

3. HYPERON PRODUCTION IN $\bar{p}A$ ANNIHILATION

An unexpectedly high Λ-hyperon production yield has been *recently observed [28-32] in the annihilation of low energy* antiprotons on nuclei. Thus, measurement of the production cross sections of Λ, $\bar{\Lambda}$ and K_S^0-mesons in the annihilation of antiprotons in Ta at 4 GeV/c [28] has revealed that $\sigma(\Lambda)$ is more than ten times greater than the corresponding cross section for the $\bar{p}p \rightarrow \Lambda\bar{\Lambda}$ reaction, multiplied by $A^{2/3}$.

Still more surprizing results were obtained in our PS 179 experiment [29-31], in which the production of neutral strange particles was investigated in the annihilation of antiprotons at 600 MeV/c and at rest in ^{3}He, ^{4}He and Ne. At these energies the production of a Λ on a single nucleon is forbidden, since the $\bar{p}p \rightarrow \Lambda\bar{\Lambda}$ reaction threshold is p_{th}=1435 MeV/c . Nevertheless, it occurs that even for annihilation of stopped $\bar{p}$, at 1.4 GeV below the threshold on a free nucleon, the yield of Λ's is quite substantial, comparable or even greater than that for the allowed K_S^0 channel. (For instance, at 600 MeV/c the ratio $R=\sigma(\Lambda)/\sigma(K_S^0)$ is $R=2.3 \pm 0.7$ and 0.94 ± 0.19 for annihilation in ^{20}Ne and ^{4}He, respectively). In Fig.5 the yield of Λ in $\bar{p}$A annihilation at rest is shown.

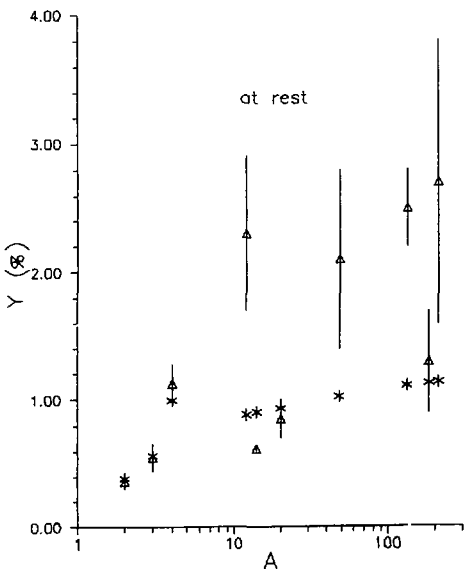

Fig.5 Yield of Λ in $\bar{p}$A annihilation at rest (in percent of all annihilation). The data are from [28-32], the asterisks indicate the result of calculations [39].

One can see that the yield is weakly dependent on A and is at the level of 1-2 % of all annihilation.

A number of models have been invoked to explain the high Λ production yield. Thus, Rafelski [33] has speculated about the possibility of the annihilation of a high energy antiproton penetrating deeply into the nucleus resulting in the formation at very low temperatures ($T \approx 60$ MeV) of some droplets of super-cooled quagma. The evaporation of these droplets should be characterized by an enhancement of strangeness production. Cugnon and Vandermeulen [34,35] have pointed out that increased strangeness production may occur not only because of the phase transition of hadronic matter but owing to the evaporation of fireballs with non-zero baryonic number. This model is, in fact, an extension of the well-working statistical model in which $N\bar{N}$ annihilation is treated like the evaporation of a B=0 fireball [19]. Annihilation in nuclei may lead to a situation when the primordial B=0 fireball captures the neighbouring nucleon (or nucleons).The subsequent decay of such B=1 fireballs is characterised by an enhancement of strangeness production simply due to an increase of the phase space of the decaying system. However, theory cannot fix the formation probability of such fireballs. Indirect estimations show that it should be less than 10% of all $\bar{p}A$ annihilations.

A lot of models [36-40] have tried to reproduce the characteristics of Λ production under the assumption that Λ is produced in annihilation meson rescattering on one of the residual nucleons, for instance, in the rescattering of $\bar{K}$:

$$\begin{aligned} \bar{p}\, N &\longrightarrow K\bar{K} + m\pi \\ \bar{K} + N &\longrightarrow \Lambda + X. \end{aligned} \tag{3.1}$$

Besides (3.1), there exists a number of channels in which Λ are produced, for instance, via Σ^0 formation

$$\bar{K} + N \longrightarrow \Sigma^0 + X \longrightarrow \Lambda\gamma + X, \tag{3.2}$$

or via $\Sigma^{\pm}$ charge exchange

$$\bar{K} + N \longrightarrow \Sigma^{\pm} + X \longrightarrow (\Sigma^{\pm}N \longrightarrow \Lambda N) + X, \tag{3.3}$$

or in two-nucleon kaon absorption

$$\bar{K} + NN \longrightarrow \Lambda + N. \quad (3.4)$$

Heavy meson rescattering may also produce Λ

$$\eta + N \longrightarrow K + \Lambda \quad (3.5)$$

$$\omega + N \longrightarrow K + \Lambda \quad (3.6)$$

Finally, ordinary pions may create Λ

$$\pi + N \longrightarrow K + \Lambda \quad (3.7)$$

It is clear that a correct analysis of all these reactions is very difficult and becomes more complicated owing to the lack of experimental information on the main characteristics of the processes, for instance, about the cross sections of reactions (3.5)-(3.6). That is the reason why the authors of different articles [36-40] obtain different results concerning the relative importance of reactions (3.1)-(3.7). However, the overall conclusion is the following: rescattering of annihilation mesons is, indeed, capable of generating a substantial yield of Λ even in low energy $\bar{p}A$ annihilation (see results shown in Fig.5).

As an example, in Table 3 the calculations [36] of different contributions to the Λ cross section are presented. From these results it is clear that the main contribution to direct Λ production is due to $\bar{K}$ rescattering which provides 30-40% of the Λ cross section. The hyperon exchange $\Sigma N \longrightarrow \Lambda N$ is also important and gives 50-40 %. If one takes into account that the Σ's are produced mainly from kaon rescattering $\bar{K}N \longrightarrow \pi\Sigma$, then, briefly, the conclusion should be the following: the high Λ yield is a consequence of the effective transformation in the nucleus of the annihilation kaons into hyperons. More than one half of all the $\bar{K}$ yield Λ's. Thus the nucleus is very effective in conversion of the kaon part of annihilation into Λ and Σ -hyperons.

This conclusion is rather important. It contradicts the quagma or fireball models [33-35] predicting the production of an additional amount of strangeness as compared with that from $N\bar{N}$ annihilation.

Table 3 . Contribution of different reactions to the Λ cross section (in percent) in $\bar{p}$ annihilation on Ta and Ne. The results of calculation are taken from [36].

Reaction	Contribution to $\sigma(\Lambda)$, %	
	$\bar{p}$Ta (4 GeV/c)	$\bar{p}$Ne (600 MeV/c
$\bar{p} + p \longrightarrow \Lambda + \bar{\Lambda}$	8.7	0
$\pi + N \longrightarrow \bar{K} + \Lambda$	20.	5.2
$\bar{K} + N \longrightarrow \pi + \Lambda$	30.6	36.9
$\eta + N \longrightarrow \bar{K} + \Lambda$	4.7	5.5
$\omega + N \longrightarrow \bar{K} + \Lambda$	2.7	18.4
$\Sigma + N \longrightarrow \Lambda + N$	50.6	37.
$\Lambda + N \longrightarrow \Sigma + N$	-17.3	-3.
$\sigma(\Lambda)_{th}$, mb	275.	19.6
$\sigma(\Lambda)_{exp}$,mb	193 ± 13.	12.3 ± 2.8

Additional support of the rescattering scheme of Λ production is given by the fact that the scheme not only allows reproduction of the overall Λ yield but also of more detailed quantities, such as momentum spectra and multiplicity distributions. For instance, in the case of $\bar{p}^3$He annihilation at rest it is possible to calculate the partial yields $Y(M,\Lambda)$ and $Y(M,K^0_S)$ of events with M charged particles associated with Λ and K_S starting directly from the yields of kaons in $\bar{p}p$ and $\bar{p}n$ annihilation. For this purpose the branching ratios of all $N\bar{N} \longrightarrow K\bar{K}\pi$ channels providing a given charged particle multiplicity M in the final state are summed up taking into account that this multiplicity may undergo changes in the rescattering process:

$$Y(M,\Lambda) = [W_p \cdot \sum_i Y^i_p(K\bar{K}+m\pi) + W_n \cdot \sum_i Y^i_n(K\bar{K}+m\pi)] \cdot P_2 \qquad (3.8)$$

$$Y(M,K^0_S) = W_p \cdot \sum_i Y^i_p(K\bar{K}+m\pi) \cdot F^i_p + W_n \cdot \sum_i Y^i_n(K\bar{K}+m\pi) \cdot F^i_n \qquad (3.9)$$

where Y^i_p (Y^i_n) are branching ratios of the channels $\bar{p}p \longrightarrow K\bar{K}m\pi$ ($\bar{p}n \longrightarrow K\bar{K}m\pi$), i stands for four different combinations of $K\bar{K}$

pairs, $F^{i}_{p,n}$ is a correction factor which takes into account the loss of kaons due to rescattering. P_2 stands for the probability of Λ production on two nucleons of ^3He, it may be derived from $\bar{p}d$ data [31]. $W_p(W_n)$ is the probability of annihilation on a proton (neutron) in ^3He. The results of calculations are given in Table 4.

From the values given in Table 4 one can see that the simple rescattering scheme allows to explain both kaon and Λ multiplicity distributions. It is noteworthy that the only input to (3.8)-(3.9) are the kaon branching ratios and the Λ production probability P_2.

Table 4. Comparison of calculated and measured charged-prong multiplicity distributions for events associated with Λ and K^0_S (from [31]). The yields of events with M charged particles are given in percentages of the total $\bar{p}^3He$ annihilation probability.

type of V^0		Number of prongs - M: 1	3	5
K^0_S	Calc.	0.35 ± 0.02	1.37 ± 0.08	0.22 ± 0.01
	Exp.	0.29 ± 0.07	1.06 ± 0.13	0.22 ± 0.07
Λ	Calc.	0.14 ± 0.02	0.43 ± 0.07	0.08 ± 0.01
	Exp.	0.16 ± 0.06	0.31 ± 0.08	0.09 ± 0.04

Another important indication for selecting the proper Λ production mechanism is provided by the momentum distributions for Λ and K^0_S. In Fig.6 the momentum distributions of Λ and K^0_S from $\bar{p}$ annihilation in ^4He at rest are shown. One can immediately see that these spectra differ from each other. Whereas the Λ momentum distribution is peaked at low momenta, around 200 MeV/c, the K^0_S spectrum resembles the ordinary kaon spectrum from $\bar{p}p$ annihilation and is concentrated around 400 MeV/c. It is remarkable that the B=1 fireball evaporation model predicts a totally different

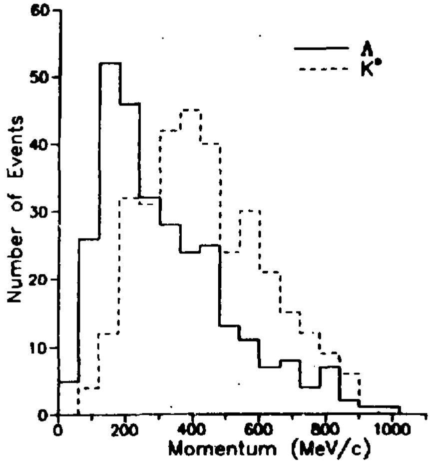

Fig.6 The momentum distributions of Λ and K_S^0 from $\bar{p}$ annihilation in ^4He at rest.

behaviour: both Λ and K_S^0 momentum distributions should be peaked around 400 MeV/c and the average momentum of Λ should be higher than that of K_S^0. At the same time, the assumption that the Λ's are created in the kaon rescattering makes it possible to reproduce the "softness" of the Λ momentum spectrum (see, Fig.7).

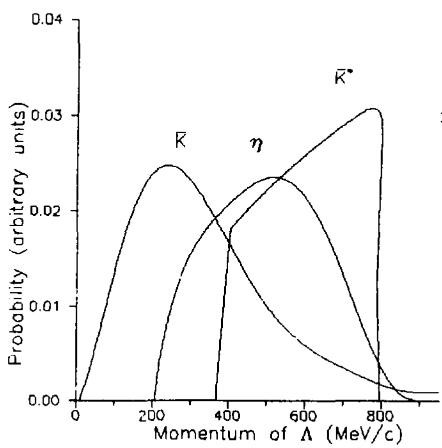

Fig.7 The results of calculation of the momentum distribution of Λ produced in the rescattering of annihilation $\bar{K}$, η and $\bar{K}^*$ mesons formed in $\bar{p}A$ annihilation at rest. All contributions are normalized to the same value.

In Fig.7 one can see the calculated momentum distribution of Λ produced in the rescattering of annihilation $\bar{K}$, η and $\bar{K}^*$ mesons formed in $\bar{p}A$ annihilation at rest. All the contributions are normalized to the same probability under the assumption that all $\bar{K}$ (or η, or $\bar{K}^*$) interact with a nucleon. One can see that the rescattering of different mesons contributes to different parts of the Λ momentum distribution. Thus the Λ's produced by $\bar{K}$ are concentrated mainly at low momenta, the Λ's from annihilation $\bar{K}^*$ should have high momenta around 700 MeV/c. The contribution from η is important in the intermediate region from 400 to 500 MeV/c.

Actually, the "softness" of the Λ momentum spectra together with the comparatively large Λ yield in $\bar{p}A$ annihilation explains the significant yield (up to 10^{-3} per annihilation) of heavy hypernuclei of ^{209}Bi and ^{238}U observed in the PS 177 experiment at LEAR [3,4]. From comparison of the absolute Λ yield and the hypernucleus formation rate one may estimate that approximately 10% of all the Λ produced in $\bar{p}A$ annihilation at rest are bound into hypernuclei. Moreover, assuming the rescattering of kaons to be the main mechanism of hyperon production in $\bar{p}A$ annihilation and knowing the $\bar{K}N \to \Lambda X$, $\Sigma^0 X$ cross sections to be approximately equal to those for $\bar{K}N \to \Sigma^{\pm} X$ one may conclude that antiproton-nucleus annihilation should also be a good source for Σ-hypernuclei production. This possibility is still unexplored in $\bar{p}A$ experiments.

4. THE RESCATTERING OF HEAVY ANNIHILATION MESONS

It was mentioned in Ch.1 that antiproton annihilation produces plenty of η, ω, ρ and another heavy mesons. One can raise the issue of the investigation of the interaction of these mesons with nucleons using $\bar{p}A$ annihilation. For example, in ref. [11] a study was suggested of the absorption of annihilation η and ω-mesons on the nucleons of residual nuclei. These reactions must be accompanied by the ejection of a pair of back-to-back correlated high energy nucleons (with energies about 300 MeV). This definite signature stimulates the experimental search of η - and ω- meson absorption to be performed with the OBELIX detector [41] under preparation now at LEAR.

Recently, the calculation of annihilation η- and ω-mesons propagation in nuclei was performed in [42]. It was shown that it is not easy to distinguish the correlated nucleon pair in $\eta+NN \longrightarrow NN$ absorption from the background of ordinary protons associated with $\bar{p}A$ annihilation. These predictions were confirmed in the experiments of the ASTERIX collaboration [23] in a study of $\bar{p}^{14}N$ annihilation at rest where the following limits on the η and ω -mesons absorption were obtained:

$$W_{abs}(\eta) < 0.05~\% , \quad W_{abs}(\omega) < 0.008~\% .$$

However, these limits are for the absorption into two protons. There are some speculations that the absorption of slow η-mesons into other channels may be preferable. These arguments are based on the results of experiments at Saclay [43] where a huge yield of η mesons (comparable with that of π^0) was discovered near the threshold of the reaction

$$p + d \longrightarrow {}^3He + \eta \qquad (4.1)$$

This means that the inverse reaction of slow η -meson absorption should also have a significant cross section. In ref.[44] it was shown that taking into account only the diagrams of two-body η absorption leads to an underestimation of the (4.1) cross section by two orders of magnitude. At the same time, inclusion of the contribution from η absorption on three nucleons provides a reasonable agreement with observed cross sections. Therefore, one cannot exclude that slow annihilation η-mesons will be effectively captured by three nucleons and the signature of η absorption must be the ejection of a correlated high-energy proton-deuteron pair.

There are suggestions to use the rescattering of annihilation mesons in nuclei to search for the H-dibaryon [45-47]. The authors have proposed to use the following reaction chain:

$$\bar{p} + {}^3He \longrightarrow \bar{K}^* K^* + 2N$$
$$\bar{K}^* + N \longrightarrow \Xi^- + K \qquad (4.2)$$
$$\Xi^- + N \longrightarrow H + X$$

Thus the suggestion is to involve via rescattering all the three nucleons of ^3He in the H-dibaryon production. (A version when the Ξ^- participating in the $\Xi^- + N \longrightarrow H$ fusion is the one bound with the neighbouring nucleus into a Ξ^- -atom is also considered (for a review, see, [45])). The main goal of the above mentioned proposals is to obtain a minimum momentum transfer in the $\Xi^- N$ interaction, i.e. to work in the region of maximum H production cross sections. It occurs that from this point of view the cascade (4.2) is more optimal than the standard reaction $K^- + {}^3He \longrightarrow K^+ + H$, where the dilambda has been searched for previously. The cascade (4.2) looks a little bit exotic. Compared to Λ -hyperon production in the kaon rescattering (3.1), processes like (4.2) are, in a sense, second-order effects, because they require additional rescattering. However the large probability of Λ production in $\bar{p}A$ annihilation provides some basis for optimism, also, in the case of searching for the H-dihyperon in $\bar{p}A$ annihilation.

At high energies ($\gtrsim$ 3-4 GeV) antiproton annihilation may produce various charmonium states. The cross sections of annihilation into charmonia are quite substantial. Estimations of charmonium production cross sections [6] give $\sigma(\psi) \approx 5\ \mu b$, $\sigma(\eta_c) \approx 0.2\ \mu b$, $\sigma(\psi(3770)) \approx 1.9\ \mu b$. It is interesting to consider the possibility opening up due to the rescattering of charmonia after high energy antiproton annihilation in nuclei. It may be relevant to the investigation of a number of nontrivial effects (see, i.e.[48,49]). For instance, one may look for supernucleus formation. A supernucleus is a nucleus in which a charmed baryon is substituted for a nucleon [7]. In this connection it is interesting to consider the proposal made by

D.E.Kharzeev [50] to use for supernucleus production the following reaction chain which starts with the formation of the lightest charmonium η_c:

$$\bar{p}p \longrightarrow \eta_c + X,$$

$$\eta_c + N \longrightarrow \Lambda_c^+ + \bar{D} \qquad (4.3)$$

A charmed hyperon is produced in the rescattering (4.3), with a relatively small momentum ($\le$ 2 GeV/c), which is lower than the threshold for inelastic Λ_c^+ interaction with nucleons. Therefore, the Λ_c^+ formed in (4.3) cannot "discharge" into D mesons and should propagate in a nucleus loosing energy through elastic collisions with nucleons of the residual nucleus or of neighbouring nuclei. Slowed down Λ_c^+ should have a substantial probability of forming a supernucleus (of course, if the Λ_c^+N interaction is constructed in a favorable way).

The production of J/ψ-particles in antiproton-nucleus annihilation may be also used for correct determination of the cross sections of J/ψ interaction with nucleons [48,49].

5. ANTIPROTON-NUCLEUS ANNIHILATION AND ASTROPHYSICS.

It is noteworthy that studies of the rescattering of annihilation mesons in $\bar{p}A$ annihilation may be essential for astrophysics, in particular, for the problem of the existence of antimatter in the early Universe. We refer the reader for essential details to books [51,52] and reviews [53-55]. Here we restrict ourselves to few brief introductional remarks.

The standard baryon-asymmetrical model of the Universe totally excludes any possibility of the existence of a significant amount of antimatter starting from the moment, approximately, $t > 10^{-3}$ s from the beginning of the Universe expansion. Its main conclusion is the following: in spite of the fact that at early stages of the Universe the concentration of antimatter was very high (approximately 10^9 times greater than the present concentration of matter), practically no relic antiprotons have survived up to now.

However, besides this commonly accepted point of view, there exist other models of antimatter evolution. For instance, according to [56], one can imagine a scenario where the baryon excess was generated in some domains, whereas in other domains an excess of antibaryons was created. This would lead to the formation of large clusters of matter and antimatter in the overall baryon-symmetric Universe. In spite of the difficulties with a consistent explanation of the evolution of matter and antimatter domains, this approach is not totally excluded by observations. Other sources of antimatter in the early Universe may be the evaporation of primordial black holes or the decays of heavy metastable particles (for instance, gravitinos) with lifetimes $\geq 10^3$ s, predicted in various models of grand unification [57-59].

Till now we have practically no experimental information about antimatter in the early Universe. It is remarkable that there is a way to acquire such information by studying the interaction of antiprotons with ^{4}He [60]. It is well known that ^{4}He is the most abundant element in the Universe after hydrogen. Its relative mass concentration is $X_{^4He} = 0.23 \pm 0.02$ [61], while the concentrations of other elements are considerably smaller (at a level of 10^{-4} and lower). The large abundance of ^{4}He is one the few observational milestones on which the hot Universe model is based. According to the standard Big-Bang scenario ^{4}He was formed in the early Universe at times greater than 10^3 s when the temperature of the Universe dropped to $T \approx 0.1$ MeV. At that time protons and neutrons became capable to take part in nuclear reactions such as $n + p \longrightarrow d + \gamma$ and the formed deuterium started to participate in successive thermonuclear transformations:

$$d + d \longrightarrow T + p\ ,\ ^3He + n, \qquad (5.1)$$

$$T + d \longrightarrow\ ^4He + n,\quad ^3He + n \longrightarrow T + p\ . \qquad (5.2)$$

Primordial nucleosynthesis practically stopped at $2\ 10^3$ s, because all free neutrons were bound in ^{4}He or had decayed.

The production of elements heavier than ^4He is suppressed (the only exclusion is ^7Li , see discussion later).

Therefore, if in the Universe at times after the *primordial nucleosynthesis era some antiprotons were present* they could have annihilated with ^4He to create deuterium nuclei as well as ^3He. The concentration of deuterium and ^3He is by four orders of magnitude lower than that of ^4He . So, the destruction of a very small amount of ^4He ($\approx 10^{-4}$) in annihilation with antiprotons would be sufficient to create all the deuterium and the ^3He observed in the Universe now. This imposes a restriction on the abundance of antiprotons in the early Universe at $t > 10^3$ s.

In a first approximation, the amount of ^3He formed as a result of $\bar{p}\,^4He$ annihilation in the early Universe is

$$\Delta n\,(^3He) = n_{^4He}\; R \;\; f_{eff} \qquad (5.3)$$

where $n_{^4He}$ represents the concentration of ^4He in the Universe,$R = n_{\bar{p}} \,/\, n_p$ is the fraction of antimatter in the early Universe and f_{eff} is the effective output of ^3He in the $\bar{p}\;^4He$ interaction.

$$f_{eff} = \frac{\sigma\,(\bar{p}\;^4He \;\longrightarrow\; ^3He + \text{anything})}{\sigma_{tot}} \qquad (5.4)$$

Assuming the amount of ^3He created as a result of $\bar{p}\,^4He$ annihilation not to exceed the abundance of ^3He observed at present

$$X_{^3He} > \Delta n\,(^3He)\; m_{^3He} \qquad (5.5)$$

one can obtain from (5.3)-(5.5) the following upper limit on the fraction of antimatter R in the early Universe

$$R < \frac{4}{3}\; \frac{X_{^3He}}{X_{^4He}\;\; f_{eff}} \qquad (5.6)$$

The only unknown value in (5.6) is the effective yield f_{eff} of ^3He from (5.4) which has been measured in the LEAR experiment PS 179 [62] . It has been shown that f_{eff} varies from 0.22 ± 0.01 to 0.33 ± 0.02 when the antiproton energy changes from 179.6 to 19.6 MeV . It follows from these data that the fraction of antimatter R in the early Universe ($10^3 < t < 10^{13}$ s) cannot be greater than

$$R \leq (0.7 - 1.1)\ 10^{-3} \qquad (5.7)$$

Otherwise the ^3He concentration in the Universe would be greater then the observed one.

The restrictions (5.7) obtained in the PS 179 experiment are the only limits on the fraction of antimatter in the early Universe ($10^3 < t < 10^{13}$s) based solely on experimental data. These limits may be significantly improved, if the experimental information on the momentum distribution of ^3He and ^3H in $\bar{p}^4He$ annihilation is known.

As one could see earlier, annihilation in the early Universe may be considered as a source of "hot" ^3He, ^3H and D nuclei, i.e. nuclei with MeV energies. We recall that after the end of primordial nucleosynthesis the temperature of the Universe was in the KeV region and that it constantly decreases. The "hot" products of $\bar{p}^4He$ annihilation should scatter on the protons and helium nuclei of the Universe plasma, and, in the latter case, they could produce new elements such as ^7Li

$$^3H + {}^4He \longrightarrow {}^7Li + \gamma$$

or ^6Li:

$$^3He + {}^4He \longrightarrow {}^6Li + p \qquad (5.8)$$

The idea is that the observed abundances of ^6Li and ^7Li are at a level of 10^{-10}, i.e. extremely low as compared with ^3He or D . This means that one can obtain an essentially more stringent limit for the possible number of antiprotons.

Now we shall estimate the lower limit. The threshold of reaction (5.8) is T = 9.76 MeV. The momentum distribution of ^3He in $\bar{p}^4He$ annihilation is poorly known, but from the results of the PS 179 experiment [18] one can estimate that approximately 10-30 % of the ^3He nuclei have an energy greater than the threshold one, i.e.

$$\Delta n\,(^3He) = (0.1 - 0.3)\ n_{^4He}\ R\ f_{eff} \qquad (5.9)$$

The *amount of* ^{6}Li, *by analogy with* (5.3), *is*

$$\Delta n(^6Li) = n_{^4He}\ \Delta n\ (^3He)\ f_{eff}(^3He\ {}^4He \longrightarrow {}^6Li+p) \qquad (5.10)$$

If the whole previous procedure is repeated, one may arrive at the conclusion, that it is possible to achieve limits for R at a level of 10^{-6}- 10^{-8}. The exact value will depend on the high-energy part of the ^{3}He spectrum in $\bar{p}^4$He annihilation, on the cross section of reaction (5.9) and on the fraction of ^{3}He which may participate in the reaction in the Universe plasma. The most obscure issue is the ^{3}He spectrum, precise measurements of which are badly needed. Such measurements are planned in the program of the LEAR PS 201 experiment with the OBELIX detector [41].

6. CONCLUSIONS AND ACKNOWLEDGEMENTS

Here we have considered only some interesting possibilities provided by the investigation of the rescattering of annihilation mesons in antiproton-nucleus annihilation. Without any doubt the list of nontrivial effects may be only extended. The real study of this class of problems is in the future.

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