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AN UPPER LIMIT FOR H-PARTICLE PRODUCTION AND SUBTHRESHOLD DOUBLE STRANGENESS PRODUCTION IN ANNIHILATION OF ANTIPROTONS ON Xe NUCLEI AT LOW ENERGY

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ABSTRACT

The results of the search for the reaction $\bar{p}Xe \to K^+K^+X$ and for $H(S=-2)$ dibaryon production in $\bar{p}Xe$ annihilations at antiproton momentum less than 0.9 GeV/c, are presented. The experiment was performed using the 700-liter Xenon bubble chamber DIANA. The data were obtained making use of about 10^6 pictures, in which $7.8 \cdot 10^5$ $\bar{p}Xe$ inelastic interactions were analysed. The following upper limits for the production probability of the stable H dibaryon in the reactions $\bar{p}Xe \to K^+K^+H(H \to \Sigma^-p)X$ and $\bar{p}Xe \to K^+H(H \to \Sigma^-p)X$ were obtained: $8 \cdot 10^{-6}$ (90%C.L.) and $6 \cdot 10^{-6}$ (90%C.L.), respectively. The properties of the observed subthreshold double strangeness reactions are discussed assuming that the main contribution comes from the ω-mesons produced in the reaction $\bar{p}N \to K\bar{K}\omega$, with the cascade process $\omega N \to \Lambda K$, and $\bar{p}N \to K\bar{K}^*$, $\bar{K}^*N \to \Xi K$, $\Xi N \to \Lambda\Lambda$. The data are compared with cascade calculations.

1. Introduction

The study of strange particle production in low-energy antiproton annihilation on nuclei opens the possibility to solve many problems associated with dynamics of strange meson production and generation of hyperons below their production threshold on free nucleons.

Cugnon and Vandermeulen[1], Dover[2], Kopeliovich[3] have emphasized that the search for final states with double strangeness in antiproton annihilations on nuclei will allow to extract the information about the presence of non-conventional processes inside the nucleus.

Applying the bag model to the six-quark system Jaffe[4] predicted the existence of relatively light dihyperons, one of which may be stable. The model predicts the S-wave flavor-singlet dihyperon (H-particle) with mass less than two masses of the Λ (within the range 2055-2230 MeV) and quantum numbers $S = -2, J^P = 0^+, I = 0$. The existence of stable H also raises the problem of the ground state of nuclei with $S = -2$, or double Λ hypernuclei, or H-nuclei.

The production of the H-dibaryon requires the double strangeness $S = -2$ exchange. Suggested by Jaffe, the most clean signature is the production of K^+K^+H final states. In the experiment by Carroll et al.[5] the reaction $pp \rightarrow K^+K^+H$ was studied at proton momentum of 5.5 GeV/c and it the cross section of H production was evaluated to be less than 30-130 nb. The observation[6] of some events of H production in pC interaction in bubble chamber requires further confirmation.

The use of the signature of two K^+ mesons to search for H in $\bar{p}A$ interactions was applied by Condo[7], and the following upper limits on probability of the reactions $\bar{p}A \rightarrow K^+K^+X$ and $\bar{p}A \rightarrow H(H \rightarrow \Sigma^- p)X$ were obtained: $5 \cdot 10^{-4}$ (90%C.L.) and $9 \cdot 10^{-5}$ (90%C.L.), respectively.

2. Experimental technique and results

A study of the reactions $\bar{p}Xe \rightarrow K^+K^+X$, $\bar{p}Xe \rightarrow K^+H(H \rightarrow \Sigma^- p)X$, and $\bar{p}Xe \rightarrow K^+K^+HX(H \rightarrow \Sigma^- p)$ was perfomed using the 700-liter Xenon bubble chamber DIANA[8]. The chamber was exposed to a separated $\bar{p}$-beam with momentum of about 1 GeV/c from the ITEP 10 GeV proton synchrotron. The chamber has dimensions $140 \cdot 70 \cdot 70 cm^3$ (density of the liquid Xenon $\rho = 2.2 g/cm^3$) and was operating without magnetic field.

The data were obtained making use of about 10^6 pictures, in which $7.8 \cdot 10^5$ $\bar{p}Xe$ inelastic interactions were found.

The antiprotons entering the chamber either annihilate in flight, due to $\bar{p}Xe$ interaction (average momentum 0.7 GeV/c) or, after energy dissipation due to ionization, at rest (momentum less than 0.4 GeV/c). A number of $5 \cdot 10^5$ $\bar{p}Xe$ annihilations in flight and $2.8 \cdot 10^5$ annihilations at rest were analysed.

The pictures were scanned to look for events with at least one K^+ meson identified by observing its decay modes ($K^+ \rightarrow \mu^+\nu$, $\pi^+\pi^o$, $\pi^+\pi^+\pi^-$, $\pi^+\pi^o\pi^o$, $\mu^+\pi^o\nu$). Because the $XeBC$ was operated without magnetic field, the positive sign of the kaon turned out by the observation of $\mu^+ \rightarrow e^+$ or $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chains at the end of the secondaries from K^+ decay.

To confirm the quality of our selection of K^+ we examined the branching ratios of all K^+ decays cited above and our results[9] for these decay modes are in good agreement with the world data. The detection efficiency of all studied particles in our experiment may be found in ref.[9] .

An overall number of 11212 annihilation events with K^+-mesons were found, what is in a good agreement with the 2% yield of K^+ meson in $\bar{p}Xe$ annihilations obtained previously[9].

All the found events with K^+mesons were analysed in order to search for additional charged strange particle ($K^+, K^-, \Sigma^\pm$). Near the annihilation vertex (region 0.2-13cm) we looked also for the $\Sigma^- p$ decay of the H-particle. K^--mesons were identified through the secondary process of Λ production in the reaction $K^-Xe \rightarrow \Lambda$X. The $\Sigma^\pm$ hyperons were identified by observing their decay mode $\Sigma^\pm \rightarrow n\pi^\pm$ and $\Sigma^+ \rightarrow p\pi^0$. In searching for H-particle we took into account that the signature of Σ^- has to be a π^- from Σ^- decay or a Λ from the reaction $\Sigma^- p \rightarrow \Lambda n$, pointing to its terminus.

After this additional scanning 774 events, containing two charged strange particles, were found. Out of this sample, 706 events had in the final states $s\bar{s}$ stringent strangeness $S = 0$ (465 events with K^+K^- pairs and 241 events with $K^+\Sigma^\pm$ pairs).

For other 57 events it was not possible to determine the sign of the second strange particle (the decay product (π, μ) of the strange particle left the chamber or when we detect $K \rightarrow e\pi^o\nu$ decay). Such events are most probably due to $\bar{p}Xe \rightarrow K^+K^-X$ reactions, in which K^--meson decayed in flight and the secondary products left the chamber. The fraction of K^--mesons decaying in flight was obtained in a special scanning of pictures of the DIANA chamber exposed to a 0.8 GeV/c K^--meson beam. The amount of K^-'s decaying in flight was found to be 5.5%. Using the yield of $\bar{p}Xe \rightarrow K^+K^-X$ reactions equal to $(0.48 \pm 0.08)\%$ at rest and $(0.26 \pm 0.06)\%$ in flight[9], the $\bar{p}$ flux, the detection and scanning efficiencies of K^+-mesons and the fraction of K^-'s decaying in flight, one obtains 64 ± 10 expected events, value in good agreement with our explanation of the nature of the observed 57 events.

However, in one of these 57 events besides $K^+K^\pm$ pair, we identified also Λ and Σ^- hyperons. So in this case we may suppose that this event corresponds to the $\bar{p}Xe \rightarrow K^+K^+\Lambda\Sigma^-X$ reaction (in flight). Besides that event, 11 events with evident two K^+-mesons (4 at rest and 7 in flight) were observed. The corresponding yields of the $\bar{p}Xe \rightarrow K^+K^+X$ reaction turned out to be equal to $3.1 \cdot 10^{-5}$(at rest) and $3.4 \cdot 10^{-5}$(in flight).

As it was mentioned, all annihilation stars containing K^+ mesons were analysed from the point of view of the presence of a H-particle decaying into Σ^-p, as well. No events were observed in $\bar{p}Xe \rightarrow K^+H(H \rightarrow \Sigma p)X$ and $\bar{p}Xe \rightarrow K^+K^+H(H \rightarrow \Sigma p)$X reactions. If we assume that the lifetime of the H is the same as that of the Λ-hyperon, the H would have a detection efficiency of 0.69 in the Σ^-p decay mode. Taking into account all the necessary corrections, the following upper limits can be obtained:

$$Br(\bar{p}Xe \to K^+H(H \to \Sigma^-p)X) < 6 \cdot 10^{-6} \quad (90\%\text{C.L.}),$$
$$Br(\bar{p}Xe \to K^+K^+H(H \to \Sigma^-p)X) < 8 \cdot 10^{-6} \quad (90\%\text{C.L.}).$$

These branching ratios are close to those in ref.[6] where the observed events were identified as H-particles.

Besides the already discussed 12 events of the type $\bar{p}Xe \to K^+K^+X$, 20 events of double strangeness production, in which the double positive strangeness was found in the K^+K^o state, were observed. The observation of such states is obviously possible only if we simultaneously detect particles with negative strangeness (a K^+K_s pair may be a $s\bar{s}$ state). The reactions $\bar{p}Xe \to K^+K^-\Lambda(\Sigma)X$ were classified as being of the K^+K^o type, because the K^o detection efficiency is less than that for the K^+-meson.

Table 1.
List of observed events with doubly strange final state in $\bar{p}Xe$ annihilations (Λ_n: $\Lambda \to n\pi^o$, K_n: $K^o \to 2\pi^o$, h: ambiguously identified meson(π or K))

$\bar{p}$ momentum interval, GeV/c	Observed final state	Yield (K^+K^+X) 10^{-4}	Observed final state	Yield (K^+K^oX) 10^{-4}
$0 \div 0.4$	K^+K^+h $K^+K^+\pi^-\pi^o$ $K^+K^+\pi^oh$ $K^+K^+\pi^oh$	0.31 ± 0.16	$K^+K^o\Lambda\Lambda$ $K^+K^o\Lambda\Sigma^-p$ $K^+K^o_n\Lambda 5p$ $K^+K^-\Lambda_n\pi^-\pi^o$	1.2 ± 0.6
$0.4 \div 0.65$	$K^+K^+\pi^-4p\gamma$ $K^+K^+\pi^-\pi^op$ K^+K^+2h K^+K^+4p	0.34 ± 0.17	$K^+K^o\Lambda\Lambda_np$ $K^+K^o\Lambda\Lambda_np$ $K^+K^o\Lambda\Lambda_n2p$ $K^+\Lambda\Lambda_n4p$ $K^+K^o_n\Sigma^-h$ $K^+\Lambda_n\Sigma^-\pi^02p$ $K^+K^o\Lambda\Sigma^-$	2.5 ± 1.2
$0.65 \div 0.9$	$K^+K^+\Lambda\Lambda_n2p$ $K^+K^+\Lambda\Lambda_n$ K^+K^+ph $K^+K^+\Lambda\Sigma^-p$	0.34 ± 0.17	$K^+K^o\Lambda\Lambda\pi^-2p$ $K^+K^o\Lambda\gamma p$ $K^+K^o\Lambda ph$ $K^+K^o\Lambda 3p$ $K^+K^o_n\Lambda\pi^o3p$ $K^+K^-\Lambda p$ $K^+K^-\Lambda_np$ $K^+K^-\Lambda 3p$ $K^+\Lambda\Sigma^-3ph$	3.1 ± 1.2

Note that the double-strangeness reactions can produce one more state with double positive strangeness only. This state is the K^oK^o state. However, in the present experiment such reactions can be observed with essentially a lower efficiency than that of the K^+K^+X and K^+K^oX states. Indeed, using the statistics of 10^5 $\bar{p}Xe$ annihilations we have no events of $\bar{p}Xe \rightarrow K^oK^oX$ reaction.

In Table 1 the list of all 32 observed events with double strangeness final states is shown. In calculating the yields, the detection efficiency of the strange particles and their neutral decay channels, as well as nonobserved K_L mesons and $\bar{p}$ flux were taken into account.

3. Subthreshold double strangeness production

Antiproton annihilation on a free nucleon at energy less than 1 GeV/c should not lead to double strangeness production. However it was shown[1] that , in principle, a cascade model which takes into account the production of any meson accompaning a KK pair, can give a double strangeness final state at the level of $10^{-4} \div 10^{-5}$. We have analysed the following cascade processes in which double strangeness can be produced:

$$\bar{p}N \rightarrow KK\bar{K}\bar{K}, \quad \bar{K}N \rightarrow \Lambda\pi \ (twice)$$
$$\bar{p}N \rightarrow \pi\pi, \quad \pi N \rightarrow K\Lambda \ (twice)$$
$$\bar{p}N \rightarrow K\bar{K}\pi, \quad \pi N \rightarrow K\Lambda$$
$$\bar{p}N \rightarrow \omega\omega, \quad \omega N \rightarrow K\Lambda \ (twice)$$
$$\bar{p}N \rightarrow K\bar{K}^*, \quad \bar{K}^*N \rightarrow \Xi K, \Xi N \rightarrow \Lambda\Lambda$$
$$\bar{p}N \rightarrow K\bar{K}\omega, \quad \omega N \rightarrow K\Lambda$$
$$\bar{p}N \rightarrow K^*\bar{K}^*, \quad K^* \rightarrow K\pi, \quad \bar{K}^*N \rightarrow \Xi K, \quad \Xi N \rightarrow \Lambda\Lambda$$

It turned out that the most important mechanisms are the following :

$$\bar{p}N \rightarrow K\overline{K}\omega, \quad \omega N \rightarrow \Lambda K \ with \ \ or \ \ without \ \overline{K}N \rightarrow \Lambda\pi$$

and

$$\bar{p}N \rightarrow K\overline{K^*}, \quad \overline{K^*}N \rightarrow \Xi K \ \ , \ \ \Xi N \rightarrow \Lambda\Lambda.$$

These channels are the most efficient ones, because the available energy in the annihilation is stored first in heavy hadrons, which can lead to double strangeness by *exothermic* reactions. We assumed that the charged states of the KK pair are given by the annihilation itself and the first ω or Ξ rescattering. Counting the possibility of having annihilation and rescattering on a proton or a neutron, one can easily calculate the probability of a given KK charged state and obtain the weight for the specific final states. Of course, this neglects the possible charge exchange between the KK pair and the rest of the system. The results are given in Table 2 for the K^+K^+X and the $K^+K^0\Lambda X$ channels, where X does or does not contain a Λ particle.

We also give in Table 2 the calculated total double strangeness yield (last column).

Table 2.

Comparison of the experimental data with calculations. (All numbers are multiplied by 10^4.)

Momentum (GeV/c)	K^+K^+X exp.	K^+K^+X calc.	$K^+K^0\Lambda X$ exp.	$K^+K^0\Lambda X$ calc.	total DS calc.
$0 \div 0.4$	0.31 ± 0.16	0.16	1.2 ± 0.6	1.59	4.3
$0.4 \div 0.65$	0.34 ± 0.17	0.19	2.5 ± 1.2	1.76	4.7
$0.65 \div 0.9$	0.34 ± 0.17	0.22	3.1 ± 1.2	1.9	5.2

As it is seen from Table 2, there is a good agreement of the experimental data with the cascade calculations. However, our analysis raises a theoretical problem. The $\omega N \rightarrow \Lambda K$, $\overline{K}^*N \rightarrow \Xi K$ and $\Xi N \rightarrow \Lambda\Lambda$ cross-sections are not known. Here, we have used reasonable assumptions. Let us recall them :

$$\sigma(\omega N \rightarrow \Lambda K, \sqrt{s}) = \sigma(\pi N \rightarrow \Lambda K, \sqrt{s}),$$

$$\frac{\sigma(\overline{K}^*N \rightarrow \Xi K, \sqrt{s})}{\sigma_{inel}(\overline{K}^*N, \sqrt{s})} = \frac{\sigma(\overline{K}N \rightarrow \Xi K, \sqrt{s})}{\sigma_{inel}(\overline{K}N, \sqrt{s})}$$

and

$$\sigma(\Xi N \rightarrow \Lambda\Lambda, \sqrt{s}) = \sigma(\Sigma N \rightarrow \Lambda N, \sqrt{s}) \times \gamma_s,$$

where γ_s is the reduction factor for strangeness production , based on low energy hadronic phenomenology[10],[11]. It is difficult to assess the uncertainty of the calculations. The latter arises from the simplifications used in the calculations and, more important, from uncertainty due to the poor knowledge of some cross-sections. An uncertainty of 30 % seems a reasonable estimate.

We investigated also the double strangeness production mechanisms that are made possible by the occurrence of $B = 1$ and $B = 2$ annihilations. Taking account of the primordial state with a Λ particle in $B = 1$ annihilations does increase the yield by about 20% , on the average. The most important fact allowed by $B > 0$ annihilations is the appearance of two Λ particles in $B = 2$ annihilations . This is in fact the most economical way, from the energetic point of view, of creating double strangeness. Using the same statistical model as in[12] , we found that the branching ratio of the $\Lambda\Lambda KK$ state in $\bar{p}3(N)$ annihilation is equal to $\sim 10^{-4}$ at rest, $\sim 2\times10^{-4}$ in the 0.6-0.9 GeV/c range. If one adds the Σ^0's coming from the $\Lambda\Sigma\overline{K}K$ and $\Sigma\Sigma KK$ channels, evaluated in the same model, the total contribution of primordial $\Sigma\Sigma KK$ raises to $\sim 5 \times 10^{-4}$ at 0.9 GeV/c.

The conclusion is that the $B = 2$ annihilations, described with the help of the statistical model of [12], are essentially largely able to account for the observed double strangeness yield. It would be, however, doubtful to attempt to fit the data with a mixture of $B = 0$ and $B = 2$ annihilations because of the crude nature of the calculations. If the figures in Table 2 are taken seriously, the $B = 2$ frequency necessary to reproduce the observed yield would lie between 0.2 and 0.4, which looks rather large.

4. Conclusion

We have analysed a sample of $2.8 \cdot 10^5$-annihilations at rest and $5 \cdot 10^5$ - annihilations in flight to search for the H-particle and to study other double strangeness reactions. As a final result we conclude :

1. There are no events of H dibaryon production in our data and the following upper limits (90% C.L.) can be put $Br(\bar{p}Xe \to K^+H(H \to \Sigma^-p)X) < 6 \cdot 10^{-6}$ and $Br(\bar{p}Xe \to K^+K^+H(H \to \Sigma^-p)X) < 8 \cdot 10^{-6}$.
2. 32 events with double strange final states (for two charged states of double positive strangeness: K^+K^+, K^+K°) were observed. The yields for these events lies between $10^{-4} \div 10^{-5}$.
3. The observed double strangeness yield seems to be explained by conventional processes, the most important of which are characterized by the transformation of most of the annihilation energy into strange particles by a chain of exothermic reactions. However, an improvement of the experimental situation is needed. A more elaborate theoretical calculation would then be justified and allow for more precise conclusions, especially for the yield of specific channels.

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