INSTITUTE OF THEORETICAL
AND EXPERIMENTAL PHYSICS

ITEP- 27–93

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Observation of subthreshold double strangeness production in $\bar{p}$ annihilations on Xe nuclei; search for stable H dibaryon

Invited Talk at the Second Biennial Conference on Low-Energy Physics LEAP'92, Courmayeur, Italy, 14-18 September 1992

Presented by A.G.Dolgolenko

MOSCOW 1993

УДК 539.12 М-16

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Preprint ITEP 93-27/

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The double strangeness production has been observed in two final states of annihilation of antiprotons at momentum less than 0.9 GeV/c on Xe nuclei: K^+K^+X (8 events) and $K^+K^0\Lambda X$ (6 events). The probabilities of the reaction $\bar{p}Xe \rightarrow K^+K^+X$ vary from $2 \cdot 10^{-5}$ (at rest) up to $7 \cdot 10^{-5}$ (in flight). The reaction $\bar{p}Xe \rightarrow K^+K^0\Lambda X$ is observed only in flight with probability $3 \cdot 10^{-4}$. The properties of the observed reactions are similar to those resulting from the cascade process with production of Ξ hyperon: $\bar{p}N \rightarrow K^*\bar{K}^*$, $K^* \rightarrow K\pi$, $\bar{K}^*N \rightarrow \Xi K$, $\Xi N \rightarrow \Lambda\Lambda$. The new upper limit on the production probability of the stable $H(S=-2)$ dibaryon in the reaction $\bar{p}Xe \rightarrow K^+K^+H(H \rightarrow \Sigma^-p)X$ was obtained to be $< 2 \cdot 10^{-5}$ (90%$C.L.$).

Fig. – 2, ref. – 9

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1. INTRODUCTION

Study of strange particle production in annihilation of low-energy antiprotons on nuclei makes it possible to solve many problems associated with dynamics of strange meson production and generation of hyperons below their production threshold on free nucleons. The significance of searching for final states with double strangeness in antiproton annihilation on nuclei to extract the information about the presence of non-conventional processes inside the nucleus was emphasized in many papers by Dover [1], Cugnon and Vandermeulen [2]. The importance of investigation of such type of reactions at antiproton momentum below the production threshold was pointed out by Kopeliovich [3]. As it is shown by Rafelski [4], the double strangeness production in antiproton annihilation on nuclei could be a signature of quark-gluon plasma formation.

Kilian [5] has proposed the H-dibaryon production mechanism in the antiproton-nucleus annihilation via the reaction chain $\bar{p}A \rightarrow K^{*}\bar{K}^{*}(A-1) \rightarrow K^{*}(A-2)\Xi K \rightarrow K^{*}K(A-3)H$ with capture of a slow Ξ hyperon on a nucleon at the third stage. The observation signature of this reaction is two K^{+} mesons in the final state.

There are only three experiments to study double strangeness production. In experiment by Condo et al. [6] on antiproton annihilation on nuclei at $\bar{p}$ momentum $< 400\ MeV/c$ there are no events with double strangeness final states ($R(\Lambda\Lambda X) < 4\cdot10^{-4}$ and $R(K^{+}K^{+}X) < 5\cdot10^{-4}$ at 90% C.L.). In paper by Miyano et al. [7] 19 events of $\Lambda\Lambda X$ production were found in $\bar{p}Ti$ annihilation at $\bar{p}$ momentum of 4.0 GeV/c, but these observations have not been explained as yet in any conventional manner. And finally in our previous experiment [8] with Xenon Bubble Chamber using 10^5 antiproton annihilations on Xe nuclei at momentum less than 1 GeV/c we searched for reactions with production of doubly strange final states and the stable $H(S = -2)$ dibaryon and did not observe events of such kind.

2. OBSERVATION OF THE REACTION $\bar{p}Xe \rightarrow K^+K^+X$ AND $\bar{p}Xe \rightarrow K^+K^0\Lambda X$ (DOUBLE STRANGENESS PRODUCTION)

The investigations on search for the reaction with double strangeness final states and stable $H(S = -2)$ dibaryon in antiproton annihilation on Xe nuclei are in progress using the 700-liter Xenon Bubble Chamber DIANA exposed to a $\bar{p}$ antiproton beam with momentum of about 1 GeV/c.

The antiproton entering the chamber can annihilate in flight (ranging from 0.9 GeV/c up to 0.4 GeV/c) and at rest after energy dissipation due to ionization in liquid xenon. As a trigger to select the annihilation stars, was observation of at least one K^+ meson accompanied by an additional strange particle $(K^{\pm}, \Sigma^{\pm}, K^0, \Lambda, \Sigma^0)$. The details of the measurement procedure and identification efficiency are presented in paper [9].

After analysis of $5.4 \cdot 10^5 \bar{p}Xe$ annihilations ($2.1 \cdot 10^5$ at rest and $3.3 \cdot 10^5$ in flight) there were found 8 events of the $\bar{p}Xe \rightarrow K^+K^+X$ reactions and 6 events of the $\bar{p}Xe \rightarrow K^+K^0\Lambda X$ reactions in our experiment.

Table 1 contains all observed events with production of many strange particles and shows all observed particles in annihilation stars. For each annihilation event we calculated the $\bar{p}$ momentum before the annihilation by the distance between the annihilation star and the annihilation peak [9]. The accuracy of the $\bar{p}$ momentum calculation is determined by the width of the annihilation peak corresponding to the dispersion of the initial $\bar{p}$ beam.

Table 1
List of observed events with doubly strange final state in $\bar{p}Xe$ annihilations

$\bar{p}$ momentum interval GeV/c	Observed final state	Yield 10^{-4}	Observed final state	Yield 10^{-4}
$0-0.4$	$K^+K^+\pi$	0.2		
	$K^+K^+\pi^-\pi^0$			
$0.4-0.65$	$K^+K^+\pi^-\gamma 4p$	0.5	K^+K^0"Λ""Λ"p	3.0
	$K^+K^+\pi^-\pi^0 p$		K^+K^0"Λ""Λ"p	
	$K^+K^+2\pi$		K^+K^0"Λ""Λ"p	
	K^+K^+4p			
$0.65-0.9$	K^+K^+"Λ""Λ"$2p$	0.7	$K^+K^0\Lambda\Lambda\pi^-2p$	3.0
	K^+K^+"Λ""Λ"		$K^+K^0\Lambda\gamma 2p$ *)	
			$K^+K^0\Lambda\pi^-$ *)	

The events are subdivided in three groups depending on $\bar{p}$ momentum: at rest events ($0-0.4\ GeV/c$), events up to the $4K$ production threshold on a free nucleon ($0.4-0.65\ GeV/c$), and events with $\bar{p}$ momentum of $0.65-0.9\ GeV/c$. The events K^+K^+X and $K^+K^0\Lambda X$ are also shown separately. The particles denoted Λ and K^0 were observed by the charged decay modes: $\Lambda\to p\pi^-$, $K^0\to\pi^+\pi^-$. The sign "Λ" denotes the proposed $\Lambda\to n\pi^0$ decay detected by 2γ observation in vicinity of the annihilation star. It should be noted that in two events (marked by *) the effective mass of $\Lambda\pi^-$ and "Λ""π^0" corresponds to the mass of the Ξ hyperon $1327\pm 15\ MeV/c^2$ and $1306\pm 20\ MeV/c^2$, respectively. We suggested $\gamma\equiv\pi^0$ as the $\Lambda\gamma$ mass is equal to $1280\pm 20\ MeV/c^2$ and is far from the Σ^0 mass.

For each group of events presented in Table 1 the probability is estimated (Yield). In this estimation we took into account the detection efficiency of the strange particles and their neutral decay channels as well as nonobservable K_L mesons. The $\bar{p}$ flux was taken to be $2.1\cdot 10^5$ for at rest events and $3.3\cdot 10^5$ shared approximately equally between two groups of events in flight.

Apparently, the antiproton annihilation on a free nucleon could not lead to appearance of the observed reactions. Therefore we considered the following cascades, which can produce our final states:

$\bar{p}N \to KK\bar{K}\bar{K}$, $\bar{K}N \to \Lambda\pi$ (twice)	$(4K)$
$\bar{p}N \to \pi\pi, \pi N \to K\Lambda$ (twice)	$(\pi\pi)$
$\bar{p}N \to K\bar{K}\pi$, $\pi N \to K\Lambda$	$(K\bar{K}\pi)$
$\bar{p}N \to \omega\omega$, $\omega N \to K\Lambda$ (twice)	$(\omega\omega)$
$\bar{p}N \to K\bar{K}^*$, $\bar{K}^*N \to \Xi K$, $\Xi N \to \Lambda\Lambda$	$(K\bar{K}^*)$
$\bar{p}N \to K^*\bar{K}^*$, $K^* \to K\pi$, $\bar{K}^*N \to \Xi K$, $\Xi N \to \Lambda\Lambda$	$(K^*\bar{K}^*)$

Fig. 1 presents the estimates of the production probability of $\bar{p}Xe \to K^+K^+X$ and $\bar{p}Xe \to K^+K^0X$ reactions as calculated by A.Sibirtsev . The probabilities were estimated using production cross sections in the elementary processes. The cross sections of $\omega N \to K\Lambda$ and $\bar{K}^*N \to \Xi K$ reactions were estimated under the assumption that $\sigma(\sqrt{s}, \pi N \to K\Lambda) = \sigma(\sqrt{s}, \omega N \to K\Lambda)$ and

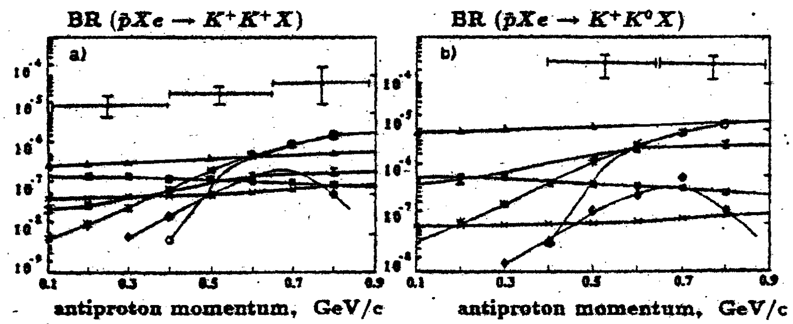

Figure 1. Branching ratios of a) $\bar{p}Xe \to K^+K^+X$ and b) $\bar{p}Xe \to K^+K^0X$ reactions. The curves are calculated by A.Sibirtsev for different processes in $\bar{p}Xe$ annihilation: ○ denotes $(4K)$ process; * denotes $(4K)$ process with 15% HEC. Cascades are shown as follows: $(\omega\omega)$ - □ , $(\pi\pi)$ - × , $(K\bar{K}\pi)$ - ◇ , $(K\bar{K}^*)$ - △ , $(K^*\bar{K}^*)$ - × . Our experimental data are presented by + .

$\sigma(\sqrt{s}, K^-p \to \Xi K) = \sigma(\sqrt{s}, \bar{K}^*N \to \Xi K)$. The Fermi motion of nuclear nucleons and high energy component (HEC) of the nucleus (for the direct process ($4K$)) were taken into account. Reactions $\bar{K}N \to \Lambda\pi$ (cascade ($4K$)) and $\Xi N \to \Lambda\Lambda$ (cascades ($K\bar{K}^*$), ($K^*\bar{K}^*$)) were not included in these calculations. As it is seen in Fig.1, the experimental points are situated higher than the calculated theoretical curve.

Only three processes have large, but still far from sufficient, probability for description of the experimental data. These processes are $\bar{p}N \to \omega\omega$ ($\omega\omega \to K\Lambda$) (cascade ($\omega\omega$)) and $\bar{p}N \to K\bar{K}^*$ or $\bar{p}N \to K^*\bar{K}^*(\bar{K}^*N \to \Xi K)$ (cascades ($K\bar{K}^*$) and ($K^*\bar{K}^*$). The direct process $\bar{p}N \to KK\bar{K}\bar{K}$ ($4K$) was estimated without taking into account the KK mass spectra. If the experimental effective mass of two K mesons (see Fig.2) is taken into account, then the estimate of the direct ($4K$) process rate will decrease. However, it should be noted that these calculations are only estimations.

Examine now also correlations of the same kinematical parameters in the observed events: K-meson momentum and the effective mass of two K mesons and two Λ hyperons. The experimental distributions on these parameters are presented in Fig.2 (the lower row). The Λ-hyperon momenta in five events, which are suggested to be the neutral decay $\Lambda \to n\pi^0$, were calculated by the momenta and emission angles of π^0 mesons. Calculating the effective mass of two Λ hyperons we obtained a striking result: within the errors the effective mass is almost the same (all quantities are in MeV/c^2): 2316 ± 12; 2264 ± 16; 2337 ± 35; 2287 ± 25; 2311 ± 16, and 2287 ± 5 for the case of two charged Λ decays. The average value is $M_{\Lambda\Lambda} = (2290 \pm 20)\ MeV/c^2$.

Fig. 2 presents also the Monte-Carlo simulation on those parameters (K momentum, M_{KK}, $M_{\Lambda\Lambda}$) for the final state produced in the cascade ($\omega\omega$), ($K\bar{K}^*$), and ($K^*\bar{K}^*$). For comparison, in Fig.2 we show the results of calculation for annihilation on $4N$ cluster: $\bar{p}4N \to KK\Lambda\Lambda N$. In these calculations we took into account the Fermi momentum of nucleons, the two- body phase space and used the $\bar{p}$ momentum equaling zero for cascade ($\omega\omega$) and equaling 0.6 GeV/c for cascades ($K\bar{K}^*$),($K^*\bar{K}^*$) and reaction $\bar{p}4N \to KK\Lambda\Lambda N$.

As it is seen in Fig.2, only distribution from the cascade process $K^*\bar{K}^*$ with production of Ξ hyperon in intermediate state are in good agreement with the experimental data. It should be noted that only

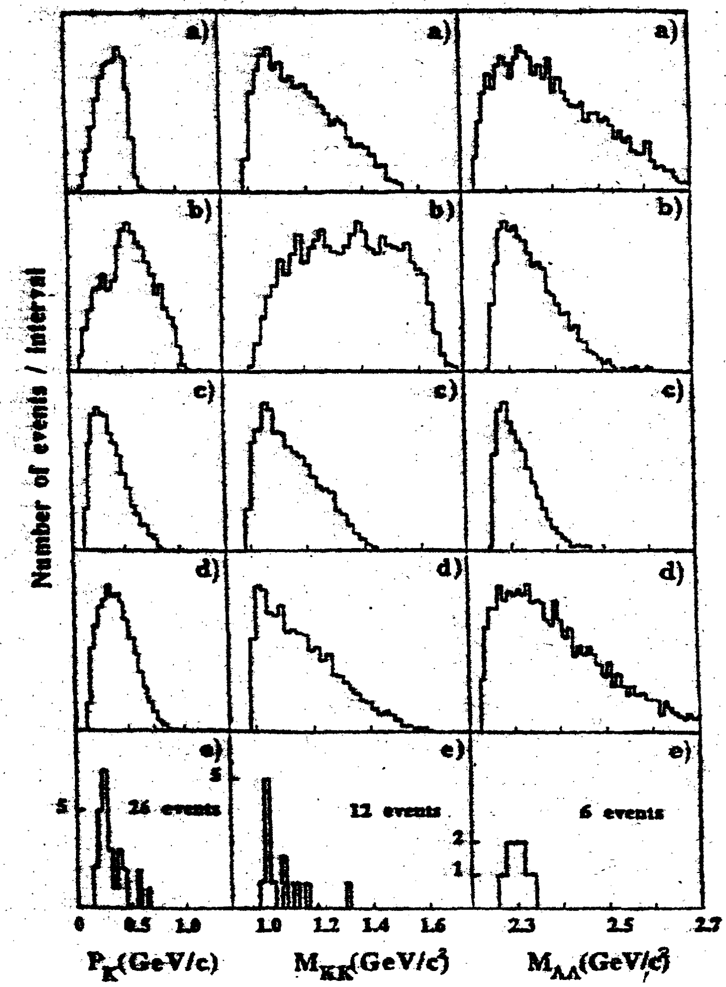

Figure 2. The spectra of the K-meson momenta (P_K), effective masses of pairs of K-mesons (M_{KK}) and Λ-hyperons ($M_{\Lambda\Lambda}$): (a-d) – Monte-Carlo simulation of different processes in $\bar{p}A$ annihilation:(a) – $\bar{p}N \to \omega\omega$, $\omega N \to K\Lambda$; (b) – $\bar{p}N \to K\bar{K}^*$, $\bar{K}^*N \to \Xi K$, $\Xi N \to \Lambda\Lambda$; (c) – $\bar{p}N \to K^*\bar{K}^*$, $\bar{K}^*N \to \Xi K$, $\Xi N \to \Lambda\Lambda; K^* \to K\pi$; (d) – $\bar{p}4N \to KK\Lambda\Lambda N$; (e) – our experimental data.

cascades $(K\bar{K}^*)$ and $(K^*\bar{K}^*)$ predict the observed strong difference between production rate of K^+K^+X and K^+K^0X final states (see Fig.1).

So, one can assume, remaining within the convenient presentations, that double strangeness production observed in our experiments can be explained due to Ξ hyperon production in the cascade process $(K^*\bar{K}^*)$. Note that this cascade is the same as the one proposed by Kilian [5] for production of H dibaryon except for the last stage: the reaction $\Xi N \rightarrow \Lambda\Lambda$ instead of capture of the Ξ hyperon by a nucleon. The distribution of the effective mass of pairs of Λ hyperons observed in our experiment are either due to kinematical restriction in the cascade $(K^*\bar{K}^*)$ process or associated with the existence of the bound $\Lambda\Lambda$ state with mass $2290 \pm 20\ MeV/c^2$.

3. SEARCH FOR STABLE H $(S = -2)$ DIBARYON DECAYING AS $H \rightarrow \Sigma^- p$.

Up to now, we have analyzed $3.2 \cdot 10^5$ annihilations ($1.4 \cdot 10^5$ at rest and $1.8 \cdot 10^5$ in flight) to search for $\bar{p}Xe \rightarrow K^+K^+H\ (H \rightarrow \Sigma^- p)X$ reaction. Four K^+K^+X events, from eight events discussed above, are involved in this material.

As earlier, in our experiment [8], the annihilation stars containing K^+ meson were analyzed also from the viewpoint of the presence of H particle decaying into $\Sigma^- p$. We have no events of such type in $3.2 \cdot 10^5$ annihilations. If we assume that the lifetime of the H is the same as that of Λ hyperon and take into account all necessary corrections, one can obtain the yield $BR(\bar{p}Xe \rightarrow K^+K^+H\ (H \rightarrow \Sigma^- p)X) < 2 \cdot 10^{-5}$ (90% C.L.).

4. CONCLUSION

The unexpected intensive subthreshold double strangeness production in the reactions of antiproton annihilation on Xe nuclei was observed. The probabilities of the reactions $\bar{p}Xe \rightarrow K^+K^+X$ and $\bar{p}Xe \rightarrow K^+K^0X\Lambda$ change from $2 \cdot 10^{-5}$ up to $3 \cdot 10^{-4}$ when the antiproton momentum is increased from at rest up to $0.9\ GeV/c$. The most probable source of the observed reactions is the cascade process through the Ξ hyperon formation: $\bar{p}N \to K^*\bar{K}^*$, $K^* \to K\pi$, $\bar{K}^*N \to \Xi K$, $\Xi N \to \Lambda\Lambda$. The observation of a narrow state in the system of two Λ hyperons with the mass equal to $M_{\Lambda\Lambda} = 2290 \pm 20\ MeV/c^2$ may be either a result of the kinematical restriction in the cascade process with Ξ hyperon production or the bound $\Lambda\Lambda$ state. A further experiment is needed to solve the problem.

In our experiment, we obtained also a new upper limit on the production probability of stable H ($S = -2$) dibaryon: $BR(\bar{p}Xe \to K^+K^+H\ (H \to \Sigma^- p)X) < 2 \cdot 10^{-5}$ (90% C.L.).

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В.В.Бармин и др.

Наблюдение подпорогового рождения двойной странности в аннигиляциях антипротонов на ядрах Хе; поиски стабильного Н-дибариона

Подписано к печати I2.04.93 Формат 60x90 I/I6 Офсетн.печ.
Усл.-печ.л.0,5. Уч.-изд.л.0,3. Тираж I60 экз. Заказ 27
Индекс 3649

Отпечатано в ИТЭФ, II7259, Москва, Б.Черемушкинская,25