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Abstract

A study of the reactions $\bar{p}\text{Xe} \to K^+K^+X$, $\bar{p}\text{Xe} \to K^+H(H \to \Sigma^-p)X$ and $\bar{p}\text{Xe} \to K^+K^+H(H \to \Sigma^-p)X$ was performed using the 700-litre xenon bubble chamber DIANA, exposed to the 1 GeV/c antiproton beam of ITEP (Moscow). From a sample of $7.8 \cdot 10^5$ antiproton annihilations at low energy in xenon nuclei 4 events were observed for the reaction $\bar{p}\text{Xe}| \to K^+K^+X$ at rest ($P_{\bar{p}} \leq 400$ MeV/c) and 8 for the same reaction in flight ($400 \leq P_{\bar{p}} \leq 900$ MeV/c). The corresponding probabilities turned out to be $3.1 \cdot 10^{-5}$ and $3.4 \cdot 10^{-5}$, respectively. No H-event was found in the two semi-inclusive reactions $\bar{p}\text{Xe} \to K^+HX$ and $\bar{p}\text{Xe} \to K^+K^+HX$. This lead to the upper limits $6 \cdot 10^{-6}$ and $8 \cdot 10^{-6}$ (90% C.L.), respectively. The corresponding upper limit for the fully inclusive reaction $\bar{p}\text{Xe} \to HX$ turned out to be $1.2 \cdot 10^{-5}$ (90% C.L.), which is about one order of magnitude lower than the actual value reported in the literature.

Since the first prediction made by Jaffe [1], within the framework of the MIT bag model, of a double strange six quark state (uuddss), flavor spin isospin singlet, called the H-particle (from hexaquark), an extensive work, both in terms of calculated properties and experimental searches has been performed. Presently, experiments are ongoing or planned in many laboratories of the world.

It may be worthy to underline the importance of the eventual discovery of the H-particle. The inability of quantum chromodynamics (QCD) to provide a quantitative description of the hadronic mass spectrum has motivated the creation of a variety of QCD inspired models, most of which predict the existence of hadron with valence quarks and gluons configurations outside the observed set of $\bar{q}q$ and qqq systems. The experimental confirmation of one of such objects would expand our knowledge of nonperturbative QCD

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and represent a dramatic confirmation of the theory itself. The implications would go beyond, from confinement theory to astrophysical consequences (for a review of the case of the H, see Ref. [2]).

Despite the many effort, at this time, at the beginning of the second half of nineties, rather twenty years since the Jaffe's calculation, the existence of the H-particle has been neither confirmed nor disproved. Three major classes of experiments have dealt with the problem:

1) (K^+K^-) reactions, of the type $K^- + {}^3\mathrm{He}$ (or A) $\to K^+ nH$ (see experiments E836 at BNL [3] and E224 at KEK [4]);

2) $(\Xi^- d)$ atom formation, of the type $K^- + p \to K^+ \Xi^-$ followed by $(\Xi^- d)$atom $\to n + H$ (see experiment E813 at BNL[5]);

3) $\Lambda\Lambda$ fusion: $p + p \to K^+ K^+ H$, where the dominant process is the $p \to K^+ \Lambda$ dissociation followed by $\Lambda\Lambda \to H$ recombination (see the first experimental investigation of the H performed by Carroll et al. [6], some months after Jaffe's paper, and the KEK experiment E248 (AIDA) [7]).

No conclusive evidence of the H has been found by these researches.

Isolate H candidates have been reported in bubble chamber experiments at Dubna [8].

The suggestion that H particles may be copiously produced in relativistic heavy ion collisions [9] has been explored in two recent Proposals at Brookhaven: the experiment E885, which explores Au + Pt collisions, and the E896, which takes advantage of Au+Au collisions. The recently published first results from E886 [10] report a null result for the possible evidence of two bound states of the H, namely H-^{3}He and H-d.

The more consistent experimental result presently available in the hunt for the H-particle is probably that obtained at KEK in a research program of double Λ-hypernuclei. If the interpretation is correct, according to this result the existence of a moderately to deeply bound H-particle should be ruled out.

Jaffe predicted that the mass for H was 2150 MeV/c^2, some 80 MeV/c^2 below the mass of the lowest-lying baryon-baryon system with $S = -2$ (i.e. the $\Lambda\Lambda$ system). Thus the H should be stable against strong decays but could decay weakly, with a lifetime depending on its mass [11]. If the H is sufficiently bound, it could be long-lived or perhaps even completely stable [12]. The observation of double hypernuclei, ${}^{A}_{\Lambda\Lambda}\mathrm{Z}$, is important in connection with the very existence of a H-particle stable against strong decays and puts a lower limit for its mass. Indeed, if in a double Λ-hypernucleus the two Λ 's form a H with a mass (m_H) much smaller than the dilambda mass, $(2m_\Lambda)$, the double hypernucleus would decay strongly into H plus a residual nucleus, ${}^{A}_{\Lambda\Lambda}\mathrm{Z} \to H + {}^{A-2}\mathrm{Z}$ (H-decay). In such a case, the branching ratio for the weak decay of the double hypernucleus would be smaller than that for the H-decay by orders of magnitude: practically it could not be observed [13]. On the other hand, if a sequential weak decay is observed, this would imply that H formation has not occurred, also in the favorable environment of two nearby Λ's or, more properly, that the mass of the H has to satisfy the condition $m_H > 2m_\Lambda - B_{\Lambda\Lambda}$, where $B_{\Lambda\Lambda}$ is the binding energy of the two Λ's in the double hypernucleus, of the order of some tens of MeV.

About thirty years ago two events were reported [14] which showed sequential weak decay of double lambda hypernuclei, but they cannot be considered convincing. Recently, the KEK experiment E176, studying stars in nuclear emulsion due to the capture at rest of Ξ^- hyperon produced in the (K^+, K^-) reaction, has directly observed [15] the sequential weak decay of the double hypernucleus ${}^{13}_{\Lambda\Lambda}\mathrm{B}$, which puts a lower limit on the mass of the H which is 2203.7 ± 0.7 MeV/c^2. The importance of the implications of the KEK result in localizing a specific H-particle to be searched has stimulated two recent new experiments at BNL, the AGS Proposals E885 [16] and E904 [17], which will follow the same hybrid spectrometer-emulsion technique employed at KEK, taking moreover advantage from the purity of the AGS 2 GeV/c kaon line.

An other interesting possibility is represented by antiproton annihilation in nuclear matter. The peculiar features of the annihilation process, characterized by multimeson (pion and kaon) final states allow strangeness transfer processes inside a nucleus, which will turn out in reactions of H formation [18]. Some years ago, Condo et al. [19] could put an upper limit upon the frequency of inclusive H-production $\bar{p}A \to HX$ in the annihilation of slow antiprotons in complex nuclei.

In this paper, the results of the analysis of a sample of low energy antiproton annihilations in xenon nuclei, which lowers the previous limit of Condo et al. [19] of about one order of magnitude, are reported.

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 $\rightarrow K^+K^+H(H \rightarrow \Sigma^-p)X$ was performed using the 700-litre xenon bubble chamber DIANA [20]. The chamber was exposed to the 1 GeV/c $\bar{p}$-beam from the ITEP 10 GeV proton synchrotron. The chamber has dimensions $70 \cdot 70 \cdot 140$ cm^3, density of the liquid xenon $\rho = 2.2$ g/cm^3 and was operating without a magnetic field.

The data reported in this paper were obtained making use of about 10^6 pictures, in which $7.8 \cdot 10^5$ $\bar{p}$Xe inelastic interactions were found. Preliminary results concerning the analysis of $3.2 \cdot 10^5$ annihilations have been reported in Ref. [21]. 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 (average 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 looking for events with at least one K^+. Half of the material was scanned twice. The K^+-mesons were identified by observing their decay modes ($K^+ \rightarrow \mu^+\nu, \pi^+\pi^0, \pi^+\pi^+\pi^-, \pi^+\pi^0\pi^0, \mu^+\pi^0\nu$). The positive sign of the kaon was found from the observation of the decay chains $\mu^+ \rightarrow e^+$ or $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ after K^+ decay. The identification of K^+-mesons had been already checked by evaluating [22] the branching ratios of all the main K^+-meson decay modes and obtaining good agreement with data from the literature. The detection efficiency of K^+-mesons, averaged over the chamber geometry, was found to be 75% . This evaluation was performed under the assumption that the K^+-momentum spectrum was the same as the K^0 momentum distribution obtained previously in the same experiment [23] and of the calculated momentum distribution of K^+-mesons from $\bar{p}p \rightarrow K^+X$ at rest [24].

An overall number of 11 212 annihilation events with K^+-mesons, corresponding to about 1.5% of all interactions, were found. This number is in good agreement with the 2% yield of K^+-mesons in $\bar{p}$Xe annihilation obtained previously [22].

The second step of the analysis was to scan again all the events with a K^+-meson in order to search for an additional charged strange particle ($K^+, K^-, \Sigma^\pm$). Near the annihilation vertex, the region 0.2–13 cm, the eventual Σ^-p decay of the H-particle was looked for. The K^--mesons were identified through the secondary process of Λ production in the reaction K^-Xe $\rightarrow \Lambda$X. The $\Sigma^\pm$ particles were identified by observing their decay mode $\Sigma^\pm \rightarrow n\pi^\pm, \Sigma^+ \rightarrow p\pi^0$. In searching for H-particles the fact that the signature of a Σ^- had to be a π^- (from Σ^- decay) or a Λ (from the reaction $\Sigma^-p \rightarrow \Lambda n$), was taken into account.

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

For 57 other events it was not possible to determine the sign of the second strange particle. These were events where the decay product (π, μ) of the strange particle had left the chamber or when a $K \rightarrow e\pi^0\nu$ decay had occurred (the charge of the "electron" could not be determined). Such events were probably due to $\bar{p}$Xe $\rightarrow K^+K^-X$ reactions in which the K^--meson decayed in flight and the secondary products left the chamber. The fraction of K^- decaying in flight was obtained in a special scanning of pictures of the chamber exposed to a 0.8 GeV/c K^- beam. The amount of K^-'s decaying in flight was found to be 5.5% of the total number of K^--mesons. Assuming for the yield of $\bar{p}$Xe $\rightarrow K^+K^-X$ reactions the values (0.48 ± 0.08)% at rest and (0.26 ± 0.06)% in flight [22], from the number of $\bar{p}$ annihilations, the detection and scanning efficiencies of K^+-mesons and the fraction of K^-'s decaying in flight, one obtains 64 ± 10 expected events, a value in good agreement with the observed 57 events.

In one of these 57 events a Σ^- and a Λ hyperon were identified. This event might correspond to the $\bar{p}$Xe $\rightarrow K^+K^+\Sigma^-\Lambda X$ reaction (in flight).

Besides that event, 11 other events with two K^+-mesons (4 at rest and 7 in flight) were observed. Examples of two of such events are shown in Fig. 1. The corresponding yields of the $\bar{p}$Xe $\rightarrow K^+K^+X$ reaction was equal to $3.1 \cdot 10^{-5}$ at rest and $3.4 \cdot 10^{-5}$ in flight. No events of this kind were found in the analysis of Condo et al. [19]. The given upper limit on the frequency was $5 \cdot 10^{-4}$.

The prediction of the intranuclear cascade model [25] for double strangeness production in low energy antiproton annihilation on nuclei is (10^{-5}–10^{-4}), in agreement with present data.

Finally, the annihilation stars containing K^+-

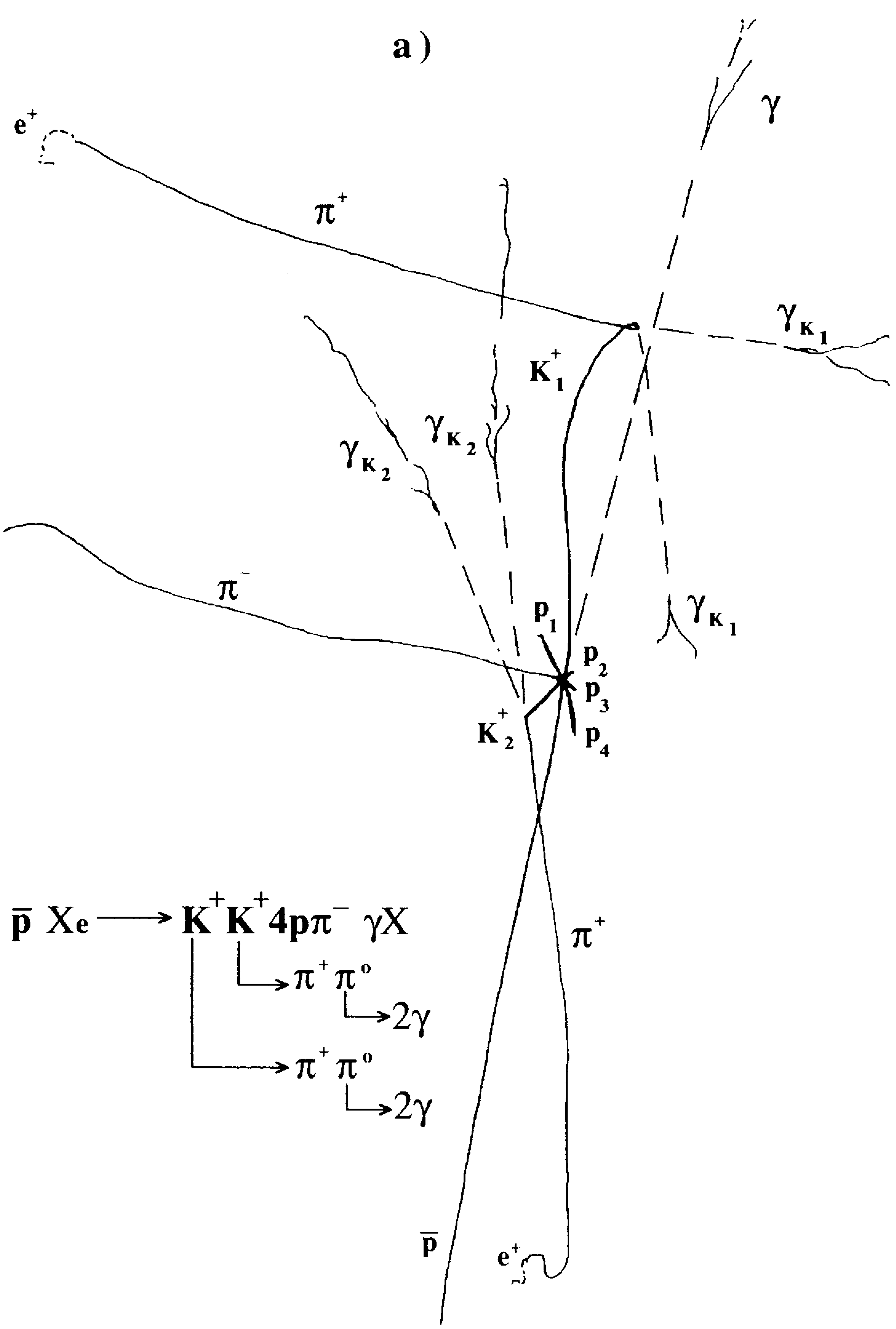

Fig. 1. Examples of events with two identified K^+-mesons: (a) $\bar{p}\mathrm{Xe} \to K^+K^+4p\pi^-\gamma X$ reaction at $P_{\bar{p}} = 0.57$ GeV/c. Both K^+-mesons stop in the chamber and decay into $\pi^+\pi^0 \to \pi^+2\gamma$. (b) $\bar{p}\mathrm{Xe} \to K^+K^+hX$ reaction at rest: h is an ambiguous charged meson (pion or kaon). Both K^+-mesons stop in the chamber and decay into $\pi^+\pi^+\pi^-$ and $\mu^+\nu$, respectively.

mesons were analysed from the point of view of the eventual presence of a H-particle decaying into Σ^-p. No events were observed in the $\bar{p}\mathrm{Xe} \to K^+HX$ and $\bar{p}\mathrm{Xe} \to K^+K^+HX$ channels. By assuming that the lifetime of the H is the same as that of the Λ-hyperon [1], the H would have a detection efficiency of 69% in the Σ^-p decay mode. Taking into account all the necessary corrections, the following upper limits could be obtained:

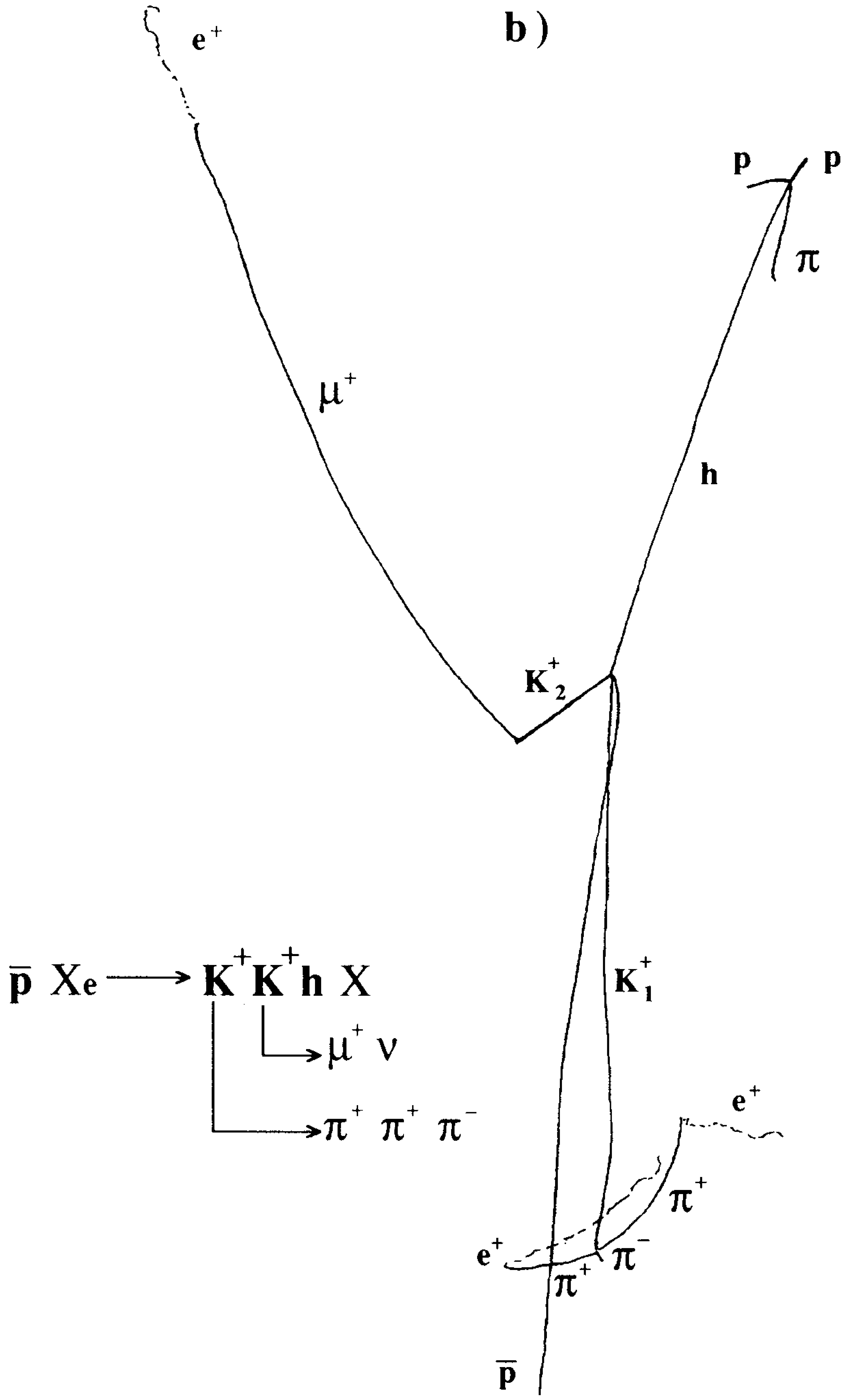

Fig. 1 — continued.

$$\mathrm{Br}(\bar{p}\mathrm{Xe} \to K^+H(H \to \Sigma^- p)X) < 6 \cdot 10^{-6}\ (90\%\ \mathrm{C.L.}), \quad (1)$$

$$\mathrm{Br}(\bar{p}\mathrm{Xe} \to K^+K^+H(H \to \Sigma^- p)X) < 8 \cdot 10^{-6}\ (90\%\ \mathrm{C.L.}). \quad (2)$$

The upper limit on the semi-inclusive process (1) can be converted into the limit on the inclusive process:

$$\bar{p}\mathrm{Xe} \to HX. \quad (3)$$

Indeed, in reaction (1), one may have, for the nonidentified particle, $X = K^+$ *or* K_0, whilst in the inclusive process (3) it is possible to have also $X = K^0K^0$. As a consequence, the overall number of channels with kaons accompanying the H are three for the semi-inclusive reaction (1) (K^+K^+H, $K^+K^0_SH$, $K^+K^0_LH$) and six for the inclusive reaction (3) (the three above, plus $K_S^0 K_S^0 H$, $K_S^0 K_L^0 H$, $K_L^0 K_L^0 H$) (assuming the independence from the charge). Therefore, from the upper limit on the semi-inclusive process, one can deduce the upper limit on the inclusive process:

$$\mathrm{Br}(\bar{p}\mathrm{Xe} \to HX) < 1.2 \cdot 10^{-5} \text{ (90\% C.L.)}$$

This value is rather one order of magnitude lower than the value reported in the literature ($9 \cdot 10^{-5}$) [19].

An obvious comment is that evidence for the H is becoming more and more elusive, which is in agreement with the substantially less bound object which emerges from the interpretation of the KEK result on double Λ-hypernuclei.

The assumption underlying the search for H-events in this measurement was a H lifetime in the $\Sigma^- p$ decay mode of the order of that of Λ-hyperon, according to the suggestion of Jaffe [1]. In the evaluation of Donoghue et al. [11], τ_H is considerably longer for nonleptonic $\Delta S = 1$ decay modes, in the range of 10^{-8} s. This would imply that no H-event could be detected in the above decay mode with the present detector.

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