CERN-EP/82-68
4 June 1982

SEARCH FOR STRANGE ($S = -2$) DIBARYONS IN THE REACTION

$K^- + d \rightarrow K^+ + MM$ AT 1.4 GeV/c

(Rome-Saclay-Vanderbilt Collaboration)

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ABSTRACT

The reaction $K^- + d \rightarrow K^+ + MM$ has been studied at 1.4 GeV/c, to search for $Q = -1$, $S = -2$ dibaryonic states, in the mass range ~ 2.1 - 2.5 GeV/c². No evidence for the presence of structures has been found and upper limits for the backward production differential cross-section for narrow states are established.

(Submitted to Nuclear Physics B)

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1. INTRODUCTION

In this paper we present the results of an experiment (PS159) performed at the CERN Proton Synchrotron to search for $S = -2$ dibaryons. The data concern the reaction

$$K^- + d \rightarrow K^+ + MM \quad (1)$$

at 1.4 GeV/c, with the outgoing K^+ detected in the forward direction. We have studied the missing-mass spectrum in the interval $\sim 2.1-2.5$ GeV/c² to search for structures as evidence of the two-body reaction:

$$K^- + d \rightarrow K^+ + H_2^- , \quad (2)$$

where H_2^- is a dibaryon with quantum numbers $B = 2$, $S = -2$, $I = 1$. Other reactions, concerning dibaryons with other quantum numbers, have also been studied, and some results already published [1].

This experiment has been stimulated by the strong interest which has been devoted in recent years to the physics of multiquark states, both from an experimental and a theoretical point of view. The interest in dibaryons is wide, since they can be interpreted either in a traditional way, as nucleons weakly bound by conventional nuclear forces, or in the framework of QCD, as "true" multiquark states bound by "colour" forces. The deuteron is the typical example of the first kind, although some recent theoretical work has suggested that it should be partially interpreted as a system of six quarks, directly interacting with each other through gluons [2].

Many experimental indications of the possible existence of dibaryonic states have been reported, but no state has been definitely established. In the more restricted field of strange dibaryons, a stronger indication comes from several experiments [3,4] on the reaction $K^-d \rightarrow \pi^-(\Lambda p)$. An enhancement in the invariant mass of the (Λp) system, just below the (ΣN) threshold, at different beam momenta up to 1.5 GeV/c, has been observed. Although its nature is still controversial, this enhancement has been interpreted as due to the existence of a dibaryon (the so-called H_1^+), with quantum numbers $B = 2$, $Q = +1$, $S = -1$, $I = 1/2$ and a mass of

$\sim 2.13 \text{ GeV}/c^2$. Recent results obtained by our Collaboration confirm, with very large statistics, the production of such a state, both in the same reaction and, for the first time, in the line-reversed reaction $\pi^+ d \rightarrow K^+ + \text{MM}$, at $1.4 \text{ GeV}/c$ [5].

The theoretical situation is also controversial. Studying all the possible baryon-baryon states obtainable in the $SU(3)$ irreducible representations of the product $8 \otimes 8$ of the baryon octet, Oakes has associated in an antidecuplet $\overline{10}$ the deuteron to other dibaryonic states: an isospin doublet of strangeness $S = -1$, a triplet $S = -2$, and a quadruplet $S = -3$. Assuming that the already-mentioned H_1^+ corresponds to the $S = -1$ isodoublet, he predicted a mass between 2.36 and $2.39 \text{ GeV}/c^2$ for the $S = -2$ isotriplet [6].

With the advent of QCD, several models have been developed that were able to describe hadrons in terms of confined coloured quarks and gluons. At the same time these models have predicted a large number of possible systems of many quarks tightly bound in different possible narrow dibaryon states. As an example, Jaffe [7], applying the MIT "bag model" to an S -wave six-quark system, has predicted the existence of a stable strange dibaryon $J^P = 0^+$ flavour singlet at $\sim 2.15 \text{ GeV}/c^2$ and of a $J^P = 1^+$ octet in the mass range 2.2 - $2.5 \text{ GeV}/c^2$. Other predictions were obtained on the basis of the same model by Mulders et al. [8]. From a different point of view Chan Hong-Mo et al. [9], using "colour chemistry" concepts, have also obtained several very narrow ($\Gamma \lesssim 10 \text{ MeV}/c^2$) six-quark states. As well as other multiquark systems, dibaryonic-states predictions have also been discussed within the "string model" framework [10].

However, after this "era of good feeling", a more careful consideration of the dynamical aspects of the problem led to a more conservative attitude about the observability of multiquark effects; a sea of broad, overlapping resonances over non-resonant background became a more popular picture [11]. Nevertheless, recent works are still claiming narrow dibaryonic states above $2.1 \text{ GeV}/c^2$ [12].

In this general atmosphere, a high-statistics, high-resolution experiment was necessary in order to clarify the situation. Simple arguments about the coherent interaction on the deuteron suggested that a first exploration, searching for

dibaryons, should be tried in the low-momentum transfer region. Furthermore, the experimental t dependence of the already-mentioned H_1^+ ($\propto \exp(-30|t|)$), see ref. [4] gives the same indication. Another important feature of the desired experimental apparatus was large flexibility, in order to allow the study of different channels, i.e. systems with different quantum numbers.

No theoretical predictions for the H_2^- production cross-section in reaction (2) are available. To attempt a rough evaluation of the order of magnitude to be expected, we can start from the experimental results obtained for the H_1^+ , interpreted as a resonant effect. Dosch et al. [13] have made an analysis of the observed (Λp) peak, using a model based on a triangle diagram production mechanism. We have extended that model to our reaction according to the diagram of fig. 1a. Besides phase-space and flux factors (KF), in this model the production cross-section depends on: a) the production amplitude $f(s', \cos \theta')$ of the hyperon at the upper vertex; b) a factor $F(t, M)$, which depends on the deuteron wave function and contains the dependence on the four-momentum transfer squared t and on the mass of the dibaryonic system $M(\Xi^- n)$; c) the scattering amplitude $T(M)$ at the hyperon-nucleon vertex. Therefore, according to this model, the backward H_2^- production differential cross-section can be written as a function of the corresponding cross-section for the H_1^+ :

$$\left[\frac{d\sigma(K^- d \rightarrow K^+ H_2^-)}{d\Omega_{K^+}^*} \right]_{\theta_{K^+}^* = 0^\circ} \approx \left[\frac{d\sigma(K^- d \rightarrow \pi^- H_1^+)}{d\Omega_{\pi^-}^*} \right]_{\theta_{\pi^-}^* = 0^\circ} \times \frac{(KF)_{H_2}}{(KF)_{H_1}} \times \frac{|f(K^- p \rightarrow K^+ \Xi^-)_{\theta_{K^+}^* = 0^\circ}|^2}{|f(K^- p \rightarrow \pi^- \Sigma^+)_{\theta_{\pi^-}^* = 0^\circ} + f(K^- n \rightarrow \pi^- \Sigma^0)_{\theta_{\pi^-}^* = 0^\circ}|^2} \times \frac{F_{H_2}^2}{F_{H_1}^2} \times \frac{T^2(H_2)}{T^2(H_1)}.$$

For the H_1^+ differential cross-section we have used the following experimental results: at ~ 0.75 GeV/c, σ_{tot} is ≈ 25 μb , while the t dependence is proportional to $\sim \exp(-30|t|)$; at 1.5 GeV/c, $\sigma_{\text{tot}} \approx 20$ μb ; the width Γ is $\lesssim 10$ MeV/c² (see references [4] and [13]). Since there is obviously no experimental information on the hyperon-nucleon scattering amplitude T , we have set $T^2(H_2) = T^2(H_1)$, i.e.

we have assumed the $(\Xi^- n)$ scattering amplitude to have the same resonant behaviour as the (ΣN) amplitude that produces the H_1^+ . The $|f|^2$ have been derived from the experimental data on Σ and Ξ^- production reported elsewhere [14,15]. Finally we have computed the F^2 following the recipe of Dosch et al. [13].

According to this model, at 1.4 GeV/c (where the "feeding" cross-section is $[d\sigma/d\Omega'_{K^+}(K^- p \rightarrow K^+ \Xi^-)]_{\theta_{K^+}=0^\circ} \approx 5 \mu\text{b/sr}$ [15] one obtains an H_2^- backward differential cross-section $[d\sigma/d\Omega'_{K^+}(K^- d \rightarrow K^+ H_2^-)]_{\theta_{K^+}=0^\circ} \approx 70 \text{ nb/sr}$ for a mass of $2.35 \text{ GeV}/c^2$. At $2.40 \text{ GeV}/c^2$ the differential cross-section drops by about a factor of two, while at $2.30 \text{ GeV}/c^2$ it amounts to $\sim 100 \text{ nb/sr}$. Once more we remark how these values are to be considered only as an order of magnitude of the effect one could expect, following a specific model and on the basis of very crude physical assumptions and rough approximations.

2. THE EXPERIMENTAL APPARATUS

The experimental set-up has been fully described earlier by us [16]. We recall here briefly (see fig. 2) that it consists of a magnetic spectrometer downstream of a 40 cm long liquid D_2 target (4 cm in diameter). It accepts particles produced in the very forward direction: $\cos \theta^* \gtrsim 0.95$, θ^* being the production angle of the triggering particle in the centre-of-mass system (c.m.s.). The momentum threshold due to the magnetic field is $\sim 0.45 \text{ GeV}/c$. At the trigger level an outgoing K^+ is defined by the coincidence $\overline{\check{C}}_1 \cdot \check{C}_2$, where $\check{C}_1$ is an aerogel Čerenkov ($n = 1.094$) and $\check{C}_2$ a water Čerenkov counter. This condition rejects pions ($\gtrsim 0.32 \text{ GeV}/c$) and protons ($\lesssim 1.1 \text{ GeV}/c$), while it accepts kaons in the range $0.56\text{--}1.12 \text{ GeV}/c$. In this way the beam particles which have not interacted in the target, and whose decay in the spectrometer would produce a high spurious trigger rate, are rejected.

Five multiwire proportional chambers (MWPCs) are used to track the outgoing particle and to reconstruct its momentum $[\Delta p/p^2 \approx 6 \times 10^{-3} (\text{GeV}/c)^{-1}]$. A set of scintillation counters (S_1, S_2, P, H_c , and a large hodoscope of nine counters H_j) is also used, both for triggering purposes and for high-resolution time-of-flight

measurements between counter S_2 and one of the nine scintillation counters H_j (FWHM ≈ 0.35 ns; average path length ~ 5.5 m).

The electrostatically separated K^- beam ($\sim 2 \times 10^4$ kaons/burst) is analysed in the magnet BM2, through a set of small MWPCs ($\Delta p/p \approx 2 \times 10^{-3}$ at 1.4 GeV/c), while an aerogel Čerenkov counter $\check{C}_0$ ($n = 1.05$), used in anticoincidence in the trigger, rejects the bulk of pion contamination. A time-of-flight system (counters S_1 and S_2 , ~ 7.5 m apart) is also installed on the beam line for the off-line selection of the incident kaons (FWHM ≈ 0.25 ns).

The electronic trigger is then given by

$$(S_1 \cdot S_2 \cdot \check{C}_0 \cdot P) \cdot \check{C}_1 \cdot (m_H = 1) \cdot H_c \cdot \check{C}_2 ,$$

m_H being the multiplicity in the H_j counter hodoscope. For a part of the time we have run without the requirement of $\check{C}_2$ in the trigger, in order to enlarge our acceptance towards lower K^+ momenta at the cost of a larger trigger rate.

A Norsk Data NORD-10S computer has been used to collect the data and to perform on line a first data reduction to reject accidental triggers, bad tracks, etc. At the end, about 1 event per machine burst has been recorded on tape to be analysed off line.

The fraction of solid angle covered in the c.m.s. by the downstream spectrometer is $\sim 1\%$. The acceptance of the apparatus has been evaluated by a Monte Carlo calculation for reaction (2), assuming that the dibaryonic state is produced isotropically in the c.m.s. The results are shown in fig. 3 as a function of the H_2^- mass, with and without the requirement of $\check{C}_2$ in the trigger. If the resonance is produced preferentially at low-momentum transfer, the value of the acceptance is strongly increased [for a mass of 2.4 GeV/c² it becomes about 20%, assuming a t dependence proportional to $\exp(-30|t|)$, as was observed in the H_1^+ effect].

Finally, the missing-mass resolution is in the range 3-5 MeV/c², depending on the momentum of the outgoing K^+ , and therefore the apparatus is particularly suited to the search for narrow structures.

3. ANALYSIS PROCEDURES AND CHECKS

After the first on-line data reduction, the sample is still contaminated by undesired events.

A first selection criterion is given by the beam time-of-flight analysis, which rejects the contamination due to events produced by residual incident pions. In fig. 4 the time of flight (TOF) separation between incident pions and kaons is shown (in this small sample of events $\check{C}_0$ was not required in the trigger).

Being left with a sample of true "K⁻ beam" events, an accurate tracking is performed through the upstream and downstream spectrometers, in order to measure the momenta and the vertex of the interaction. This allows to suppress events in which the outgoing K⁺ decays (almost 50% of the total) as well as residual spurious triggers due to K⁻ beam decays and not rejected by the trigger logic.

The remaining sample is then analysed by the downstream time-of-flight system. In fig. 5 the plot of the mass squared, M^2 , of the outgoing particle versus its momentum p is shown for a partial sample of events. The value M^2 is computed by combining the TOF value, the momentum p , and the path length L , as obtained by the MWPC system:

$$M^2 = p^2 \left[(\text{TOF} \cdot c/L)^2 - 1 \right] .$$

In this plot the data from all the hodoscope counters H_j are gathered together (after having experimentally determined the appropriate constant of each single counter H_j). The separation between pions, kaons, and protons is clear, and kaons can be selected with a negligible contamination.

Finally, only the events produced in the deuterium target are selected. In fig. 6 the z coordinate (along the beam axis) of the vertex is shown for the total yield, together with the cuts chosen to select good events. Owing to the finite resolution in the reconstruction of the vertex position, these cuts still allow for a background due to events produced out of the target, i.e. in the upstream and downstream counters. In order to estimate this contamination we have taken

empty target runs. From these data we have evaluated the contribution of the "out of target" events to be about 10%. Conversely, the z cuts produce a loss of true "in target" events of the order of 5%.

The performance of the apparatus and of the analysis procedure has been tested in several reactions on a hydrogen target.

For example, the Σ^+ mass, measured as the missing-mass in the reaction

$$\pi^+ + p \rightarrow K^+ + MM$$

at 1.4 GeV/c, is shown in fig. 7; the experimental resolution is $\sigma \approx 3.5 \text{ MeV}/c^2$, in agreement with *a priori* evaluations. In the same reactions the mass scale calibration has been also tested, leading to small corrections to the position of the chambers and to the magnetic fields.

An experimental check of the over-all detection efficiency (taking into account both hardware and software losses) was also obtained, although less stringently, by comparing our results on hydrogen with available experimental data on the differential cross-section for Σ^+ backward production [17]. This efficiency factor turns out to be about 0.35, with a 25% systematic uncertainty mainly due to the large errors in the published data.

4. RESULTS

The data presented in this paper have been collected during a running period of about 14 months. The total incident flux is $4.1 \times 10^{10} K^-$.

The missing-mass spectrum of our total sample (8767 events) is shown in fig. 8. A dibaryonic state should appear in the missing-mass spectrum as an enhancement above the physical background, which is mainly due to the interaction of the incident K^- with a single nucleon of the deuteron. The primary contribution comes from the reaction

$$K^- + d \rightarrow K^+ + \Xi^- + n. \quad (3)$$

The solid line is the result of a fit in which the background coming from reaction (3), as evaluated by Monte Carlo calculation, is considered, together

with the "out of target" contribution ($\sim 5\%$). A constant background ($\sim 4\%$) is included in order to account for residual contaminations due to beam decay in the spectrometer or to other physical processes, such as, for example, K^+ production through double charge exchange and an intermediate regeneration of $\bar{K}^0 \rightarrow K^0$, according to the scheme

which has a smooth behaviour as a function of the K^+ missing mass. The contribution from the reaction

whose shape has been evaluated by a simple phase-space Monte Carlo calculation, was also added, but its contribution to the fit was negligible.

The experimental distribution as a function of $(t - t_0)$ is shown in fig. 9, where t_0 is the four-momentum transfer squared for the K^+ at 0° . The solid line is in this case the result of a simpler fit, where only the background coming from reaction (3) is considered. This spectrum clearly shows that the acceptance of the apparatus is strongly peaked in the forward direction.

As can be seen in fig. 8, the agreement between the fitted curve and the experimental data is not completely satisfactory. This is due to several different reasons. First of all it should be noted that the region around $2.3 \text{ GeV}/c^2$ is where a sharp contribution due to Ξ^- production on the free hydrogen of the surrounding material would be expected. We have tried to account somehow in the fit for such "out of target" contamination, but its actual shape in missing mass is largely unknown. Furthermore, besides the usual and unavoidable simplifications used in the Monte Carlo calculation to reproduce the performance of the experimental apparatus, other factors affect the shape of the spectrum. Our computation of the physical background coming from reaction (3) has been based on the diagram of fig. 1b alone, which does not fully reproduce reactions on deuterium (see, for

example, the paper by Alberi et al. [18] from which we have taken the parametrization for the neutron spectator momentum distribution). In addition, the shape of the missing-mass spectrum may be strongly affected by the angular and energy dependence of the Ξ^- production on a proton, as at the upper vertex of the diagram of fig. 1b. The differential cross-section of such a process is poorly known in the kinematical region covered by our experiment: we have used a rough estimate obtainable from the data of ref. [15].

Despite the somewhat unsatisfactory agreement between the data and the fitted curve, we conclude that there is no evidence for the presence of narrow structures in the explored mass range, either above or below the $(\Xi^- n)$ threshold, the few events below threshold being fully consistent with other possible mechanisms, such as reaction (4).

The sample of events taken without Čerenkov counter $\check{C}_2$ in the trigger is more appropriate for the study of the higher mass region (fig. 10). This sample of 2498 events corresponds to an incident flux of $1.04 \times 10^{10} K^-$. Again, there is no evidence of any structure.

Therefore, if one assumes that the data are completely accounted for by the background mechanisms discussed above, an upper limit for the production differential cross-section at 180° in the c.m.s. for the H_2^- can be evaluated. In fig. 11 the upper limit at 95% confidence level for the production of a narrow resonance is shown, as a function of the mass, for both data samples. The values of the upper limits have been basically obtained from the standard deviation $\sqrt{N_i}$ of each bin, weighted on a Gaussian distribution corresponding to the experimental mass resolution, i.e. they are valid for resonances with a width negligible with respect to the experimental resolution.

The corresponding upper limits for the total cross-section are strongly correlated to the momentum-transfer dependence at production; as an example, around $2.4 \text{ GeV}/c^2$ the upper limit ranges from $\sim 200 \text{ nb}$ (in the hypothesis of isotropic production) to a few nanobarns for a t dependence proportional to $\exp(-30|t|)$.

It is interesting to notice that in our data no effect is present around $\sim 2.48 \text{ GeV}/c^2$: in that region, an enhancement of several μb of σ_{tot} in the $(\Xi^- p)$ invariant mass spectrum has been claimed recently [19] from the analysis of bubble-chamber data on the reaction $K^- d \rightarrow K^0 \Xi^- p$.

Finally, we can extract from our sample the differential cross-section of process (3) for a K^+ produced at 0° in the c.m.s. From the fit discussed previously we obtain:

$$\left[\frac{d\sigma(K^- d \rightarrow K^+ \Xi^- n)}{d\Omega_{K^+}^*} \right]_{\theta_{K^+}^* = 0^\circ} = 2.4 \pm 0.6 \mu\text{b/sr}$$

at $1.4 \text{ GeV}/c$.

5. CONCLUSIONS

From this high-sensitivity experiment we conclude that there is no evidence for the existence of $Q = -1$, $S = -2$ dibaryonic states, in the mass range $2.1\text{--}2.5 \text{ GeV}/c^2$. The 95% confidence-level upper limit for the production differential cross-section at 180° in the c.m.s. of a narrow resonance ($\Gamma \lesssim 8 \text{ MeV}/c^2$) is of the order of $5\text{--}40 \text{ nb/sr}$, depending on its mass (see fig. 10).

Acknowledgements

We are very grateful to CERN for its warm hospitality and to the PS staff for the very efficient operation of the machine during all the running period.

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Figure captions

- Fig. 1 : a) Triangle diagram for the production of an H_2^- state through a hyperon-nucleon final-state interaction.
b) Direct E^- production on the proton of the deuteron.
- Fig. 2 : The experimental set-up.
- Fig. 3 : Acceptance of the experimental apparatus for the H_2^- dibaryon production as a function of its mass, assuming an isotropic production in the c.m.s. The solid line is calculated with the Čerenkov $\check{C}_2$ in the trigger, the dashed line without $\check{C}_2$.
- Fig. 4 : Čerenkov $\check{C}_0$ pulse height versus beam particle time of flight (in this sample, $\check{C}_0$ was not required in the trigger).
- Fig. 5 : Measured momentum p of the outgoing particle versus its calculated mass squared M^2 (see text).
- Fig. 6 : Distribution of the vertex position along the beam axis (z) for the total sample (solid line) and for an empty-target sample (dashed line). The arrows show the cuts applied to the data to select "in target" events.
- Fig. 7 : Missing-mass distribution for the reaction $\pi^+p \rightarrow K^+ + MM$ at 1.4 GeV/c.
- Fig. 8 : Missing-mass spectrum for the reaction $K^-d \rightarrow K^+ + MM$ at 1.4 GeV/c. In this sample the Čerenkov $\check{C}_2$ was required in the trigger. The solid curve is the result of a fit (see text). The thresholds for the different possible channels are also shown. Only (E^-n) and $(\Sigma^-\Lambda)$ channels have been taken into account in the fit.
- Fig. 9 : Four-momentum transfer squared $(t - t_{0o})$ distribution $[t_{0o} = t(\theta_{K^+}^* = 0^\circ)]$. The solid line gives the Monte Carlo calculation for the reaction $K^-d \rightarrow K^+E^-n$.

Fig. 10 : Missing-mass spectrum for the sample without the Čerenkov $\check{C}_2$ in the trigger (solid histogram). The dashed spectrum is obtained by requiring this signal from $\check{C}_2$ in the off-line analysis. The thresholds for the different possible channels are also shown.

Fig. 11 : 95% confidence-level upper limit of the c.m.s. differential cross-section for the production at 180° in the c.m.s. of a narrow ($\Gamma \lesssim 8 \text{ MeV}/c^2$) dibaryon. Solid line for the total sample (Čerenkov $\check{C}_2$ in the trigger); dashed line for the sample of fig. 10 (without $\check{C}_2$ in the trigger).

Fig. 1

Čerenkov Counters

$\check{C}_0$: Aerogel ($n=1.05$)

$\check{C}_1$: Aerogel ($n=1.094$)

$\check{C}_2$: Water with wave-length shifter

Multi Wire-Proportional-Chambers

$Ch_{11,12,13,14,15}$: 1mm spacing MWPC

$Ch_{1,2,3,4}$: 2mm spacing MWPC

Scintillation Counters

S_1 : PILOT-U Scintillator

S_2 : PILOT-U Scintillator

P : NE 110 Scintillator

$H_j (j=1, \dots, 9)$: PILOT-U Scint.

H_c : NE 110 Scintillator

5x10x0.5 cm³

5x10x1 cm³

4x3x0.3cm³

25x75x2.5cm³

225x55x1 cm³

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11