Scanned with permission from the publisher:

Examples of the production of K^0 , $\bar{K}^0$ and K^+ ,

K^0 pairs of heavy mesons / Cooper, W Alan, Filthuth, Heinz, Newth, J
Anthony, Petrucci, Guido, Salmeron, Roberto Aureliano, Zichichi, Antonino
CERN-57-42

Published in Nuovo Cimento 5 (1957) pp 1388-1397

From Carmen Vasini <vasini@sif.it>

To Jens Vigen <Jens.Vigen@cern.ch>

Subject Re Request for permission to reproduce published material

Dear Jens Vigen,

we are glad to grant you permission to reproduce the material requested provided full credit is given to the source

Kindest regards

Carmen Vasini

W A COOPER, etc
 1957, Giugno
Il Nuovo Cimento
 Serie X, Vol 5, pag 1388 1397

Examples of the Production of (K^0, K^0) and (K^+, K^-) Pairs of Heavy Mesons

W A COOPER, H FILTHUTH, J A NEWTH, G PETRUCCI,
 R A SALMERON and A ZICHICHI

CERN Geneva

(ricevuto il 14 Gennaio 1957)

Summary — Two simple nuclear interactions that produce pairs of K mesons are described and discussed. They are interpreted as examples of the processes $n + p \rightarrow K^0 + \bar{K}^0 + n + p$ and $n + p \rightarrow K^+ + \bar{K}^- + n + n$ where $\bar{K}^-$ is the anti particle of the K^0 meson.

- - - -

1 - Introduction

The production, in elementary reactions, of pairs of K-mesons without other strange particles has been predicted theoretically by GELL-MANN and PAIS ⁽¹⁾. Two examples of (K^+, K^-) pairs, interpreted in this way, have been observed in emulsion experiments ^(2,3). One event seen in a cloud chamber attached to the Berkeley accelerator has been interpreted as a $(K^0, \bar{K}^0)$ pair in which only one of the K^0 -mesons was seen to decay ⁽⁴⁾.

During a systematic study of the associated production of heavy mesons and hyperons in a cosmic-ray cloud chamber we have found two examples

⁽¹⁾ M GELL MANN and A PAIS: *Proceedings of the Glasgow Conference on Meson and Nuclear Physics* (1954), p 342

⁽²⁾ M W FRIEDLANDER, D KEEFE and M G K MENON: *Nuovo Cimento*, **2**, 666 (1955)

⁽³⁾ M CECCARELLI, M GRILLI, M MERLIN, G SALANDIN and B SECHI: *Nuovo Cimento*, **2**, 828 (1955)

⁽⁴⁾ W B FOWLER, G MAENCHEN, W M POWELL, G SAPHIR and R W WRIGHT: *Phys Rev*, **103**, 208 (1956)

of very simple nuclear interactions that give rise to pairs of K-mesons. In one case both the K-mesons are neutral, in the second case one is neutral and the other positively charged. The three neutral K-mesons are all seen to decay.

The importance of these observations is that they provide evidence to support the theoretical prediction that K^0 -mesons should exist in two states with opposite « strangeness » ^(1,5)

2 – Selection of events

In studying the production of heavy mesons and hyperons we have drawn heavily on the earlier work of JAMES and SALMERON ⁽⁶⁾. They pointed out that nuclear interactions of low multiplicity occurring inside a cloud chamber were the most profitable to study. The probability of detecting V particles produced in such interactions is relatively large and the chance of two V particles being plurally produced, that is, produced in separate elementary reactions, is small. They also showed that nuclear scattering, at least of Λ^0 -particles, made the interpretation of production processes occurring in heavy nuclei extremely difficult. For this reason, and to reduce further the probability of plural production, they proposed the use of a light material inside the cloud chamber.

We have a collection of 60 000 cloud chamber photographs taken at the Jungfraujoch for all of which there was a solid plate placed across the centre of the chamber. For 5 000 photographs the plate was of lead, 30 mm thick, for 35 000 it was copper, 12 mm thick, and for the last 20 000 photographs a graphite plate 25 mm thick was used.

Nine nuclear interactions in these plates produced two strange particles. Table I lists these events giving the nature of the strange particles and the type of interaction.

The neutral V-events have been classified as compatible or incompatible with Λ^0 -decays. Events that cannot be Λ^0 decays are assumed to be the decays of neutral K-mesons. All these K^0 -decays could be due to θ^0 -particles but the measurements do not exclude any of them being « anomalous » decays. In fact, among the thirteen neutral V-events of Table I there is no identified Λ^0 -decay. Eight of the V-events are K^0 -decays and the other five could be either Λ^0 - or K^0 -decays.

Three of the nine nuclear interactions listed in Table I produce two K-mesons. Of these three, two have no fast charged secondary particles;

⁽⁵⁾ Discussion in Sect. 8, *Proceedings of the Sixth Rochester Conference* (1956)

⁽⁶⁾ G. D. JAMES and R. A. SALMERON: *Phil. Mag.*, **46**, 571 (1955)

therefore the probability that these interactions are elementary is very high. The description and discussion of these two events are given in the following sections.

TABLE I - *Interactions in the cloud chamber producing associated strange particles*

Picture No	Identity of Strange Particles (*)	Details of Interaction			
		Material	Primary	Fast Secondaries	Slow Secondaries
VB 536	$K^0 + K^0$	Graphite	Neutral	0	1
SN 1534	$K^0 + K^+$	Copper	Neutral	0	0
TS 200	$K^0 + V^0$	Graphite	Charged	0	1
TF 1561	$K^0 + K^0$	Copper	Charged	1 (+ ?)	3 (+ ?)
TD 1183	$K^0 + V^0$	Copper	Charged	1 + e p	0
SO 1073	$K^+ + V^+$	Copper	Charged	1	1
TB 249	$K^0 + V^+$	Copper	Neutral	3	0
TH 1018	$V^0 + V^0$	Copper	Neutral	5 + e p	8
SL 496	$V^0 + V^+$	Copper	Neutral	5	4

(*) In this column K^0 stands for a V^0 particle that cannot be a Λ^0 particle and V^0 for a neutral V particle that could be either a Λ^0 or a K^0 particle. The two K^+ mesons are slow moving particles whose decay is not observed; they are identified from momentum and ionization. The three V^+ particles could be either K mesons or hyperons.

In event TF 1561 the position of the interaction in the cloud chamber makes it unlikely that all the charged secondary particles are observed. The abbreviation "e p" stands for "electron positron pair".

3 - Description of the events

3.1 Event VB 536 (Plate 1) - This event shows two neutral V-particles and a single slow proton coming from an interaction in graphite. The interaction is produced by a neutral particle, presumably a neutron. The two V-events are not Λ^0 -decays. All the four decay products of these K^0 -particles have high momenta and we can only give lower limits to the Q -values of the decays. Assuming decay into two π -mesons, these lower limits are 77 MeV and 31 MeV.

On the assumption that the two particles are θ^0 -mesons, their momenta can be calculated quite accurately from the geometry of the decays. The values are 1400 MeV/c and 2550 MeV/c. The corresponding times of flight are $1.3 \cdot 10^{-10}$ s and $0.4 \cdot 10^{-10}$ s.

In the cloud chamber there are also the tracks of two fast particles that enter the chamber from above. These tracks are nearly vertical and if we assume that the neutron causing the interaction in the graphite plate was associated with them it is possible to make a dynamical analysis of the interaction.

3.2 Event SN 1534 (Plate 2) – In this event a non decaying K^+ -meson and a V^0 particle are the only visible products of a nuclear interaction in copper. The primary of the interaction is again neutral but there are no fast charged particles to indicate its direction.

The identification of the K^+ meson from this interaction is based on measurements of momentum and ionization and is extremely convincing since, on the same photograph, another K^+ -meson which stops in the copper plate producing a characteristic S event has similar momentum and ionization.

The positive secondary particle from the V^0 decay is a slow light meson and the decay cannot, therefore, be a Λ^0 -decay. The negative secondary particle has a high momentum and, again, only a lower limit to the Q value of the decay can be calculated. Assuming decay into two π -mesons this lower limit is 146 MeV. If the V -particle is a θ^0 -meson, the momentum of the θ^0 -meson is 1090 MeV/c and its time of flight before decay is $1.6 \cdot 10^{-10}$ s.

The detailed measurements made on the two events and the method of identifying the various particles involved are given in the appendices.

4 – The production reactions

Accepting the phenomenological theory of strange particles ⁽¹⁾ and its predictions about the allowed processes of associated production where the total «strangeness» (S) is conserved, there are three ways in which two K mesons may arise from a nuclear interaction.

First is the possibility of plural processes. In our events one could assume that each K meson ($S = +1$) was produced with a Σ^- or Λ hyperon ($S = -1$) in the well established reactions leading to (Y, K) association. The strictness with which we have selected interactions of low multiplicity is strong evidence against this interpretation. If it were correct, four strange particles would have been produced in each interaction but no fast charged particle. Moreover, if a charged Σ hyperon had been produced either it or its charged decay product would certainly have been seen. The hyperon most likely to escape detection is the neutral Λ^0 -particle and it is improbable that we should see no Λ^0 -decay if, in fact, a Λ^0 -particle was produced with each of the four K -mesons.

A second possible interpretation involves the production of a Ξ -particle ($S = -2$) and two K -mesons each with $S = +1$. An example of this process has been observed ⁽²⁾. The known Ξ^- particle would almost certainly have been detected in either of our two events. But there are theoretical

⁽¹⁾ J. D. SORRELS, R. B. LEIGHTON and C. D. ANDERSON: *Phys. Rev.*, **100**, 1457 (1955).

W A COOPER, H FULTHUTH, J A NEWTH, G PETRUCCI,
R A SALMERON and A ZICHICHI

Plate 1 - Event VB 536 *A*, *B* and *C*, *D* are two K^0 decays and *P* is the track of a proton from the nuclear interaction producing the K^0 mesons. The nuclear interaction occurs in a graphite plate and the primary particle is presumably a neutron. The two fast particles entering the chamber at the top suggest that the neutron was part of a nearly vertical shower. The measurements of the various tracks are given in Table II.

W A COOPER, H FILTHUTH, J A NEWTH, G PETRUCCI,
R SALMERON and A ZICHICH

Plate 2 - Event SN 1534 A K^+ meson and a K^0 meson are produced in a nuclear interaction in copper. Track C is that of the K^+ meson, A is a heavily ionizing positive light meson and B is the negative secondary from the K^0 decay. Track D is that of a K^+ meson which stops in the copper plate and decays into a charged secondary particle (E). The similarity between tracks C and D makes possible the identification of particle C as a K^+ meson. The measurements of the event are given in Table III.

arguments for the existence of a Ξ^0 -particle whose immediate decay products (Λ^0, π^0) are also uncharged. The reactions

$$(1) \quad \begin{cases} n + p \rightarrow \Xi^0 + K^0 + K^0 + p & (\text{VB } 536) \\ \text{and} \\ n + p \rightarrow \Xi^0 + K^+ + K^0 + n & (\text{SN } 1534) \end{cases}$$

could thus account for our two events. These reactions are rather elaborate constructions to explain our events and since the events can be interpreted without introducing unobserved strange particles we prefer not to invoke the hypothetical Ξ^0 particle.

The third, and most plausible, interpretation is that the events show the production of pairs of K-mesons with opposite strangeness ($S = +1$ and $S = -1$). If we follow the theory of GELL MANN and PAIS ⁽¹⁾ these pairs would consist of a particle and an anti particle and the production reaction would be

$$(2) \quad \begin{cases} n + p \rightarrow K^0 + \bar{K}^0 + n + p & (\text{VB } 536) \\ \text{and} \\ n + p \rightarrow K^+ + \bar{K}^0 + n + n & (\text{SN } 1534) \end{cases}$$

From the point of view of the dynamics of the reactions only there is little difference between (1) and (2) since both the Ξ^0 -particle and the neutron are heavy particles.

Assuming that reactions (2) are the correct interpretation of the two events, a lower limit may be set to the energy of the incident neutron in each case. For event VB 536 this limit is 5.7 GeV and for SN 1534 it is 3.8 GeV. If, further, we assume the direction of the incident neutron in event VB 536 to be that of the two fast particles in the top of the cloud chamber the dynamics of reaction (2) can be fully analyzed and the neutron energy is uniquely determined as 7.3 GeV. These values may be compared with the threshold energy of 2.5 GeV for reaction (2).

More detailed calculations of the dynamics of the reactions are not very reliable but one can say with confidence that the inelasticity of the neutron-proton collision is not more than about 50% in either of the events. In VB 536 this means that the secondary neutron travels forwards with considerable energy (~ 2 GeV) after the interaction. The same conclusion would hold for the Ξ particle from reaction (1) and this is the reason for our confidence that a Ξ^- particle would have been observed had it been produced. In event SN 1534 one of the two heavy particles that are not observed must be fast but the other can have a low energy.

5 – Discussion

It would be of great value to know whether the K^0 -mesons produced in our two events could be identified as θ^0 -particles or not. Unfortunately the experimental measurements are not very helpful.

Concerning the dynamics of the decays, only lower limits can be set to the Q -values in all three cases. For the two V^0 -decays in event VB 536 the $Q(\pi\pi)$ -values are > 77 MeV and > 31 MeV. The $Q(\pi\pi)$ -value for the V^0 event in SN 1534 is > 146 MeV. All one can say, therefore, is that the K^0 -decay in SN 1534 is not a τ^0 -decay.

The geometry of event VB 536 is of interest since the planes of the two V^0 -decays intersect in a line which, itself, intersects the proton track within the limits of experimental error. If either V^0 decay were a three body decay this would be an improbable situation. It therefore seems likely that both are decays into two bodies or, at least, that any third, neutral, particle is produced with a low momentum.

The lifetimes of the three K^0 -mesons are all of the order of 10^{-10} s. This provides no direct evidence for identifying them as θ^0 -mesons whose mean lifetime is 10^{-10} s since the cloud chamber would not have contained the decays if the lifetimes had been much longer than they were. Indirectly, one can argue that if one of the K^0 -mesons had a very long mean lifetime ($\sim 10^{-8}$ s) the probability of observing an event like VB 536 would be extremely small.

From the above points it is clear that all three K^0 mesons could well be θ^0 -mesons but there is little direct evidence for this identification. In our calculations we have assumed that they are all θ^0 -mesons.

Finally, it is worth commenting on the general importance of the pair-production of K -meson. In an earlier paper ⁽⁸⁾ we showed that the positive excess among charged K -mesons in the cosmic radiation was about 3.5:1. We pointed out that this implied that the frequency of reactions in which pairs of K -mesons were produced was comparable with that of processes leading to a hyperon and a K^+ -meson. For the neutral V -particles we find a similar situation. The observations in Table I include more K^0 -mesons than Λ^0 -hyperons. Among single V^0 -events we also find an excess of K^0 -decays. Considering only V -particles produced in carbon, the K^0 particles exceed the Λ^0 -particles by a factor of two or three. This excess is not simple to interpret but processes of the type recorded in this paper could clearly explain it.

⁽⁸⁾ W. A. COOPER, H. FILTHUTH, J. A. NEWTH and R. A. SALMERON: *Nuovo Cimento*, **4**, 390 (1956).

6 - Conclusions

The two events reported in this paper extend our knowledge of the production processes of heavy mesons. To the best of our knowledge, they are the first examples that have been observed of (K^0, K^0) and (K^+, K^0) pairs produced in simple interactions where the K-mesons have been identified directly.

The events are evidence that K^0 mesons with both positive and negative strangeness exist. That this should be so was predicted by GELL-MANN and PAIS who suggested that the K^+ - and K^- -mesons were particle and anti-particle with $S = +1$ and $S = -1$ and that, likewise, the K^0 -mesons should exist in two states as particle and anti-particle with $S = +1$ and $S = -1$.

We interpret our observations, therefore, as being examples of $(K^0, \bar{K}^0)$ and $(K^+, \bar{K}^0)$ pairs produced in elementary neutron-proton interactions.

There seems to be good evidence that the production of K-meson pairs of this type is an important process at cosmic-ray energies.

* * *

We are grateful for the facilities provided for us at the Jungfraujoch Research Station where the photographs discussed in this paper were taken. In particular, we have received great help from the manager of the Station, Mr HANS WIEDERKEHR.

Among our colleagues we should like to thank Mr S O LARSON for the construction of apparatus and assistance in running it, Mlle E JOVET for making measurements of the photographs and Mr A H CHAPMAN, Mr G D JAMES and Mr H STEINER who all helped us with our work at the Jungfraujoch.

In writing this paper we have had the good fortune to be able to discuss it with Dr B D'ESPAGNAT and Dr J PRENTKI.

APPENDIX A

Event VB 536

The measurements made on this event are given in Table II. None of the four tracks from the two neutral V-events shows a measurable curvature and the lower limits to the momenta of the four particles are given by the maximum detectable momentum. This is assumed to be proportional to the square of the track length for tracks less than 22 cm long and is equal to 4 GeV/c for tracks of this length or longer.

TABLE II - Measurements made on event VB 536

a) Tracks

Track	Sign	Ionization (I_0)	Length (cm)	Momentum (MeV/c)	Calculated Momentum (MeV/c) (*)
<i>A</i>	$\pm$	< 2	8 0	> 530	540 ± 40
<i>B</i>	$\pm$	< 2	7 0	> 410	930 ± 50
<i>C</i>	$\pm$	< 2	12 5	> 1300	1450 ± 150
<i>D</i>	$\pm$	< 2	13 0	> 1400	1160 ± 150
<i>P</i>	+	3 to 6	11 5	330^{+144}_{-77}	—

b) Angles

Tracks	Angle ($^\circ$)	Tracks	Angle ($^\circ$)
<i>A B</i>	33.0 ± 1	<i>C D</i>	18.5 ± 1
$V_{AB} A$	20.5 ± 2	$V_{CD} C$	7.0 ± 3
$V_{AB} B$	12.5 ± 2	$V_{CD} D$	11.5 ± 3
$V_{AB} V_{CD}$	5.0 ± 1	Plane (<i>AB</i>) Plane (<i>CD</i>)	55 ± 2

The ionization densities given in column 3 are visual estimates. The momenta in column 5 are for tracks *A B C* and *D* the values of the maximum detectable momentum calculated for tracks of different length as explained in the text.

The angles have been calculated on the supposition that the V particles come from an interaction in the graphite plate located by track *P* and the planes of the two V decays.

(*) The momenta in column 6 have been calculated using the angles given in the table and assuming that the two V decays are θ^0 decays.

Neither V^0 -event can be a Λ^0 -decay since the value of $P_- \sin \varphi$ (where P_- is the momentum of the negative secondary and φ is the opening angle of the V^0 -decay) are both greater than 120 MeV/c ($^\circ$). This criterion is completely satisfactory for V_{CD} but for V_{AB} the value of $P_B \sin \varphi$ is > 217 MeV/c if the value of P_B is taken equal to the maximum detectable momentum. If P_B were half the maximum detectable momentum the value of $P_B \sin \varphi$ would be less than 120 MeV/c allowing interpretation of V_{AB} as a Λ^0 -decay.

If we accept the interaction in the carbon plate as the origin of the V -particles there is complete certainty that V_{AB} is not a Λ^0 -decay. From the angle measurements given in Table II the momenta of particles *A* and *B* can be calculated assuming V_{AB} to be a Λ^0 -decay. One finds that either *A* or *B* should be the track of a proton with momentum 260 MeV/c or less. A proton of this momentum has an ionization of $10I_0$ and would easily be recognised.

Using the measurements in Table II lower limits to the $Q(\pi\pi)$ -values for the two V^0 -events can be calculated. The values are 106 MeV for V_{AB} and 236 MeV for V_{CD} if the momenta of the four particles *A, B, C* and *D* are all taken to be equal to the appropriate maximum detectable momentum. If we

($^\circ$) J. P. ASTBURY: *Nuovo Cimento*, **12**, 387 (1954)

make the pessimistic assumption that all the momenta are, in fact, only half the maximum detectable momentum the lower limits to the Q -values become 31 MeV and 77 MeV respectively. It is thus possible that the two V-particles are θ^0 -particles with $Q(\pi\pi) = 215$ MeV but they could also be «anomalous» decays. If we assume that they are θ^0 -particles their momenta and also the momenta of the secondary particles can be calculated from the angle; in Table II. The momenta of the V-particles are found to be 1400 MeV/c and 2550 MeV/c; the corresponding momenta of the secondaries are given in column 6 of Table II.

APPENDIX B

Event SN 1534

The measurements made on this event are given in Table III. The V^0 -decay cannot be a Λ^0 -decay since the positive secondary particle has a mass less than 500 m. Assuming the negative particle to have a momentum equal to the maximum detectable momentum the $Q(\pi\pi)$ -value for the decay is 276 MeV. If the momentum is half the maximum detectable momentum, the $Q(\pi\pi)$ -value is reduced to 146 MeV. Again, the V-event could well be a θ^0 -decay and, in this case, it could not be a τ^0 -decay ($Q(\pi\pi) \leq 80$ MeV). If the decay is assumed to be a θ^0 -decay the negative particle's momentum is found from P_+ and φ to be 1050 MeV/c and the momentum of the θ^0 -particle is 1090 MeV/c.

TABLE III - *Measurements made on event SN 1534*

Track	Sign	Ionization (I_0)	Length (cm)	Momentum (MeV/c)	Mass (m_e)
<i>A</i>	+	3 to 6	13.0	64 ± 5	220 to 430
<i>B</i>	$\pm$	< 2	13.0	> 1400	—
<i>C</i>	+	3 to 6	23.0	220 ± 15	770 to 1400
<i>D</i>	+	4 to 8	10.0	155^{+34}_{-26}	560 to 1400
<i>E</i>	+	< 2	19.0	188 ± 12	< 520
<p>Angle $\widehat{AB} = 26^\circ \pm 1^\circ$ Angle $\widehat{V_{AB}C} = 69.5^\circ \pm 2^\circ$</p> <p>The measurements of this event have been made as described in the text. The masses of the various particles have been found by combining the estimated ionization densities with the measured momenta. The angle $\widehat{V_{AB}C}$ is found on the assumption that the line of flight of the V^0 particle intersects track C in the copper plate.</p>					

The track *C* cuts the plane of the V^0 -decay in a point which lies inside the copper plate. This point lies very close to the continuation of track *B* — as would be expected if the V-event were a θ^0 -decay and the θ^0 -particle were produced with particle *C* in the copper plate.

From the measurements made on track C it is apparently due to a heavy meson. An isolated track of this sort could not be reliably identified because of the uncertainties attached to visual estimates of ionization. Fortunately, event SN 1534 shows a second heavy meson (track D) which stops and decays in the copper plate giving a single charged secondary (E). The resemblance between tracks C and D is so close that C can be confidently identified as a K^+ -meson.

Analysis of the S-event shows that the particle E was emitted from the decay point of D with a momentum of (204^{+18}_{-15}) MeV/c if E is assumed to be a μ -meson or with (207^{+19}_{-15}) MeV/c if it is assumed to be a π -meson. The decay is probably an example of $K_{\pi 2}$ -decay ($p^* = 205$ MeV/c) but could also be $K_{\mu 2}$ -decay ($p^* = 236$ MeV/c).

•
RIASSUNTO (*)

Si descrivono e discutono due semplici interazioni nucleari producenti coppie di mesoni K . Si interpretano come esempi dei processi $n+p \rightarrow K^0 + \bar{K}^0 + n + p$ e $n+p \rightarrow K^+ + \bar{K}^0 + n + n$, dove $\bar{K}^0$ è l'antiparticella del mesone K^0 .

(*) Traduzione a cura della Redazione