NUCLEAR INTERACTIONS OF K-MESONS

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Received December 6, 1954

(Communicated by Prof. Bernard Peters, F.A.SC.)

Abstract

Fast K-mesons (τ- as well as K_{μ}-mesons) with energies between 150 and 250 MeV can cause nuclear disintegrations and lose a substantial fraction of their kinetic energy without losing their identity. The character of the interaction in three of the four cases discussed here exhibit a remarkable degree of similarity.

The nuclear capture of a K-meson at rest is discussed. The nature and distribution of prongs in the capture star suggest that a Λ°-hyperon may have been formed during the capture process.

I. Introduction

During recent investigations with large emulsion block detectors[1] exposed to cosmic radiation at high altitude, we have observed examples of the interaction of fast K-mesons with nuclei and have also obtained some additional information on the interaction of negative K-mesons at rest. In this paper we describe five events:

(*a*) three have been interpreted as nuclear interactions of fast K-mesons,

(*b*) one event can be attributed either to Coulomb or to nuclear interaction of a K-meson, and

(*c*) one represents an example of a negative K-meson which gives rise to an unusual capture star when at rest.

For the sake of convenience and completeness in describing the available information on these events, we have adopted the following conventions. The tracks are classified as white, grey or black as given in Table I. This is,

TABLE I

Type of track	Symbol	Grain density interval
White	w	$g \leqslant 1\cdot5\, g_{pl}$*
Grey	g	$1\cdot5\, g_{pl} < g < 4\, g_{pl}$
Black	b	$g > 4\, g_{pl}$

* g_{pl} is the grain density at the plateau of the ionization curve as measured by grain counting tracks of fast electron-positron pairs.

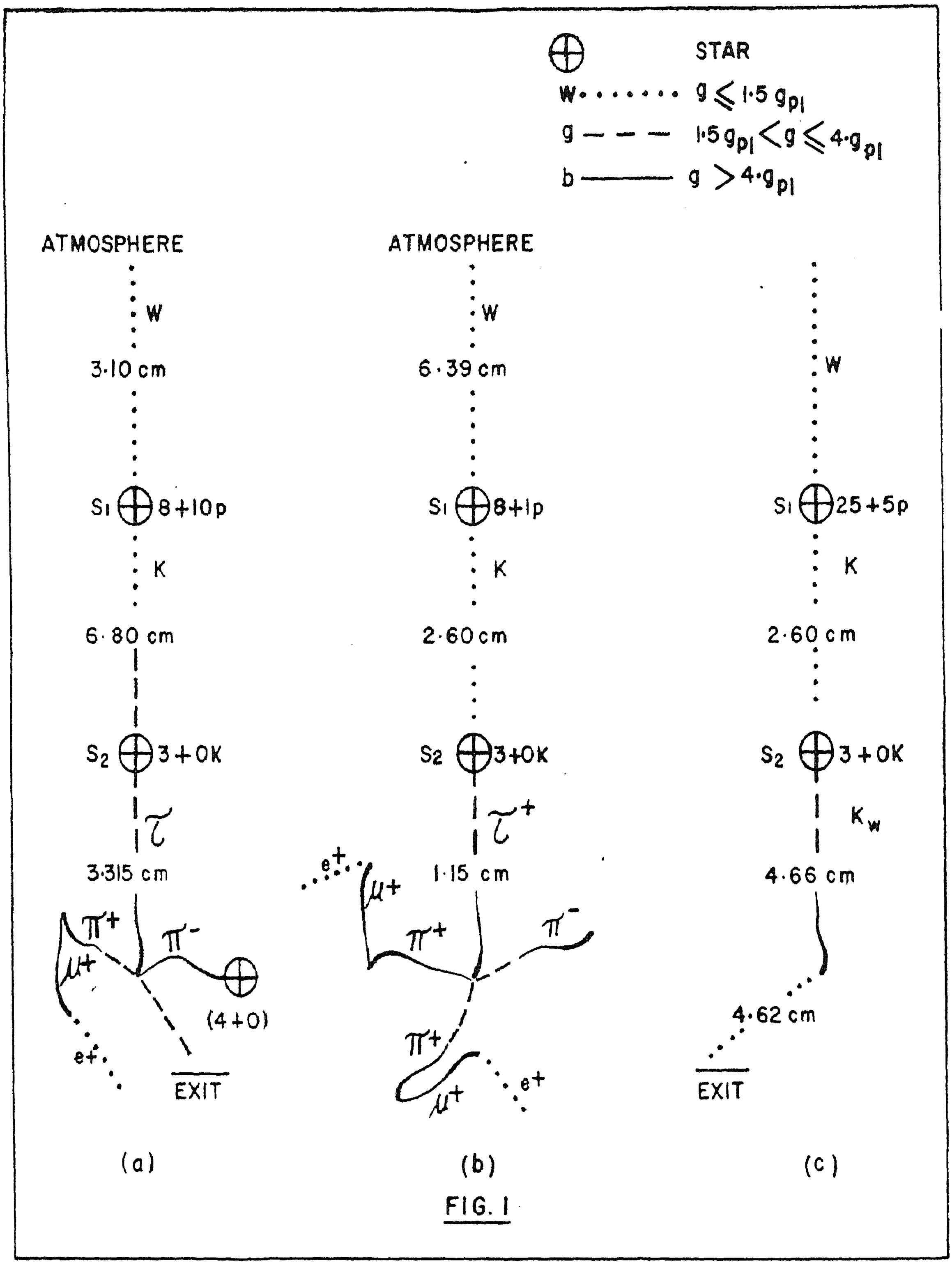

FIG. 1

therefore, a classification of particles according to specific ionisation irrespective of mass and charge.

If the *mass* of the particle is known, the symbols L, K and Y, with their conventional meanings,[2] are used. If in addition the *exact decay scheme* is known, the particle is designated by its Greek letter (μ, π, τ, Λ, etc.). If the decay process cannot be completely described, we add the available information on the decay process as subscript. With these conventions, we designate a K-meson disintegration into a relativistic singly charged particle as K_w and if the identity of this charged decay product is established as electron, μ-meson or π-meson, the parent particle is designated as K_e, K_μ or K_π respectively.† When the particle produces a capture star at the end its range, the subscript σ will be used.

II. NUCLEAR INTERACTIONS OF FAST K-MESONS

In the course of tracing stopped K-mesons to the point of their creation, we have observed three events which exhibit similar features. Schematic diagrams of these are given in Fig. 1. A relativistic singly charged particle enters the stack of emulsions (Figs. 1 *a* and 1 *b*) and produces a high energy nuclear disintegration S_1. In each case one of the fast particles emerging from S_1 is shown to be a K-meson and causes a second star S_2, from which a τ-meson is emitted. Fig. 1 *c* shows a very similar event in which the primary was not traced to its entrance point in the stack; here, however, we are dealing with a different type of K-meson designated as K_w. As indicated in the figures, the chain of events extends over a distance of about 10 cm. which is of the order of the dimensions of the emulsion blocks used ($12 \times 15 \times 15$ cm. and $8 \times 15 \times 15$ cm.). Measurements made on the three S_1 and S_2 stars and on the particles which connect them will now be described.

(1) *The Primary Stars* S_1 *and the Interconnecting Particles*

In Table II, we have listed the measurements made on the S_1 stars and the interconnecting particles.

It is apparent from the observed grain densities of the tracks produced by the interconnecting particles, that they are non-relativistic and singly charged and do not have enough energy to *produce* the S_1 stars. Therefore, they are *emitted* from S_1 and caused the S_2 stars.

All the tracks of secondary particles associated with the S_1 stars with grain density $g > 1{\cdot}2\, g_{pl}$ were followed until they left the stack or were brought to rest. We did not find any other unstable particle decaying in flight or at rest while in the stack. One grey track in event No. 1 stopped suddenly in the middle of the emulsion without showing the usual increase in grain density or scattering and without giving rise to any charged particle.

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† Our nomenclature differs, therefore, from that used by Gregory *et al.*[3] These authors designate K_μ as a particle which emits a μ-meson in a *two body* decay process, while in our system, K_μ implies only that the charged decay product was identified as μ-meson.

TABLE II

Event No.	Parent Star S_1	Tracks in Star S_1		Interconnector $S_1 - S_2$			
		Tracks	Fate	Total obs. Range	Av. length per plate	Grain density near S_1 star g/g_{pl}	Grain density near S_2 star g/g_{pl}
1	$8+10p$	Primary	Enters stack	6·80 cm.	1·305 mm.	1·43± ·055	1·67±·055
		9 whites	Not traced				
		1 white	Interconnector				
		3 greys	Leave stack				
		1 grey	Suddenly stops in middle of emulsion				
		4 blacks	End				
2	$8+1p$	Primary	Enters stack	2·60 cm.	2·10 mm.	Average Grain Density = 1·285 ± ·055	
		1 white	Interconnector				
		1 gre	Ends				
		7 blacks	End				
3	$25+5p$	Primary	Not traced	2·60 cm.	1·625 mm.	Average Grain Density = 1·35 ± ·055	
		4 whites	Not traced				
		1 white	Interconnector				
		8 greys	Leave stack				
		2 greys	Interact				
		5 greys	End				
		10 blacks	End				

(2) *The Secondary Stars S_2*

The observations made on the S_2 stars are listed in Table III.

It may be of interest to note that in each S_2-star there are only three secondary tracks, one K-meson, one recoil and one black prong which in all cases looks heavier than a proton although the track lengths are insufficient to make a reliable mass measurement. All these particles were brought to rest in the stack.

(3) *Identification of the Interconnecting Particles*

As mentioned earlier the interconnecting particles move towards the S_2-stars each of which emits a K-meson. We can show that in all the three examples, the interconnecting particle itself must be a K-meson.

TABLE III

Event No.	S_2 Star	Tracks in Star S_2			Energy loss suffered by the inter-connector in MeV.	Angle between the Inter-connector and the K-meson
		Range	Identity	Kinetic Energy in MeV.		
1	3+0K	6·80 cm.	Interconnector (assumed mass 965 m_e)	148		
		1·315 cm.	τ-meson*	47	101	78°
		836μ	Probably deuteron	17		
		2·4μ	Recoil	..		
2	3+0K	2·60 cm.	Interconnector (assumed mass 965 m_e)	246		
		1·15 cm.	τ^+-meson*	44	202	38°
		45μ	Probably deuteron	2·8		
		2·0μ	Recoil	..		
3	3+0K	2·60 cm.	Interconnector (assumed mass 965 m_e)	219		
		4·66 cm.	K_w-meson †(assumed mass 965 m_e)	102	117	105·5°
		2000μ	Probably dueteron	28		
		1·6μ	Recoil	..		

* All but one of the decay products of the two τ-mesons come to rest in the stack; the τ-mesons suffer the normal decay into three π-mesons. Q-values and other details will be reported separately.

† The decay track of K_w leaves the stack after traversing 4·62 cm. and has an average length of 3·56 mm. per plate. Its grain density is 0·975 ± ·04 and $p\beta = 150 \pm 16$ MeV./c. One could, therefore, identify this K-meson with the $\theta^{\pm}$ - meson:

$$\theta^{\pm} \rightarrow \pi^{\pm} + \pi^{0}$$

and

$$M_{\theta^{\pm}} = M_{\tau} = 965\, m_e.$$

Firstly, it is clear that they cannot be L-mesons because L-mesons of comparable initial velocity will exhibit much larger changes of grain density in traversing comparable distances. Therefore, considering only known particles, we are left with the following possibilities. The interconnecting particles are:

(*a*) protons, hyperons, deuterons or tritons, or

(*b*) they are K-mesons.

Let us take the first alternative. From each S_2-star an identified K-meson is emitted; the collision between a proton, deuteron or triton and a nucleon in the target nucleus must, therefore, result in the creation of a K-meson. We now consider whether for the observed velocities of the interconnecting particles there is sufficient energy available to create a K-meson of mass 965 m_e at rest in the centre of mass system of the incoming particle (proton, deuteron or triton) and a nucleon in the target nucleus. In order to decrease the energy requirement to its lowest possible value we assume that the nucleon which was struck had a kinetic energy of ~ 20 MeV inside the target nucleus and that its direction of motion was such as to meet the incident particle head-on. (We assume here that the K-meson is created in a single collision between one of the nucleons of the incident deuteron or triton and one nucleon of the target nucleus.) In Table IV we give the calculated threshold energies for the production of a K-meson by a proton, deuteron or triton in such collisions and compare them with the energies estimated from the observed grain densities of the three interconnecting particles.

TABLE IV

Assumed incident particle	Proton	Deuteron	Triton
Threshold energy to produce a K-meson of mass 965 m_e	790 MeV.	1400 MeV.	1775 MeV.
Kinetic energy of interconnector from the observed grain density			
Event No. 1	262 ± 15 MeV.	524 ± 30 MeV.	786 ± 45 MeV.
No. 2	384 ± 18 MeV.	768 ± 36 MeV.	1152 ± 54 MeV.
No. 3	354 ± 18 MeV.	708 ± 36 MeV.	1062 ± 54 MeV.

It is apparent from Table IV that in none of the three events, the energy available in the C.M. system of the colliding particles is sufficient to create a K-meson. Therefore, in each case the interconnecting particle itself must be a K-meson. We have also made direct mass measurements on the interconnecting tracks; as shown below the results are consistent with this conclusion.

(4) *Direct Mass Measurements on the Interconnecting Tracks*

(*a*) *Variation of Grain Density along the Track of the Interconnecting Particles.*—Event No. 1 is the only case where a significant increase in grain density along the track of the interconnector is observed (Table II). The grain densities measured near the stars S_1 and S_2 are $1 \cdot 43 \pm 0 \cdot 055$ and $1 \cdot 67 \pm 0 \cdot 055$ respectively. The observed increase in grain density after a length of 6·1 cm. corresponds to a particle of mass 800–2300 m_e. The other two interconnectors do not show any significant increase in the grain density, nor do we expect such increase in the observed amounts of absorber traversed if the particles are K-mesons.

(*b*) *Scattering* versus *Grain Density*.—As is seen from Table II, although the total track lengths available for measurements are large, the average lengths per plate of the interconnectors are 1·305, 2·1 and 1·625 mm. only. At energies with which we are dealing here and for the observed steepness of their tracks the emulsion distortion becomes very important and measurements of coulomb scattering become unreliable. For the slowest interconnecting particle we obtained from scattering a mass value of 820 ± 180 m_e after making distortion correction using higher order differences.[13] In the other two cases we obtained mass values $\sim 500\, m_e$. Though these values are not very reliable, they are not inconsistent with other findings.

(5) *Interpretation of the Events*

We have shown in the previous section that in all these events the interconnectors are fast K-mesons which cause the S_2-stars and from each S_2-star a τ or K_w is ejected. The events, therefore, represent nuclear interactions of fast K-mesons. If we assume that the interconnecting K-mesons are of the same type as those emerging from their interaction stars, we may infer that τ and K_w-mesons interact strongly with nuclear matter and that their structure is such that they can retain their identity in collisions where energies upto ~ 200 MeV. are exchanged, that is, energies larger than the rest mass of π-mesons.

It must, however, be pointed out, that since these events were discovered by tracing K-mesons backward from the point at which they came to rest, events in which fast K-mesons interact, and lose their identity in the process would not have been discovered in our investigation.

(6) *A Fourth Possible Case*

A particle is emitted from a star of the type 13 + 1*n*. After a traversal of 5·66 mm. of emulsion, the track suffers a deflection of 138°. After an additional 6·25 mm. the particle comes to rest, and emits a relativistic secondary. Scattering measurements on the track before and after the deflection show that the mass values obtained for both the sections is $\sim 1000\, m_e$. Therefore, in our nomenclature the track is designated as a K_w-meson. The grain density and scattering measurements show that the energy loss is of the order of a few MeV. only. At the point of deflection, there is a short track, very likely due to a recoiling nucleus. The event could, therefore, be interpreted either as a nuclear scattering or as a coulomb scattering of a K_w-meson by a heavy atom in the emulsion.

III. CAPTURE OF A NEGATIVE K-MESON AT REST

We have previously reported[4] nuclear interactions of negative K-mesons at rest. We have now observed an additional case which has some peculiar, though possibly accidental, characteristics. A K-meson is ejected from a nuclear disintegration of the type $7 + 8\,p$ and brought to rest in the same emulsion giving rise to a capture star. Details of measurements made on the K^--meson, its parent star and the capture star are given in Table V.

TABLE V

Present Star	Range of K^-	Mass of K^- from Range vs. Scattering	Capture Star				
			Total Range		Av. length/plate	Identity	Kinetic Energy
$7+8\,p$	2·9 mm. (in one plate)	$1040 \pm 200\ m_e$	1	2·833 cm.	1·18 mm.	π^--meson	44·4 MeV.
			2	1·734 cm.	5·78 mm.	Proton	74·3 MeV.
			3	2·7μ	..	Recoil	..

The mass of particle (2) emitted from the capture star was estimated from scattering measurements using the constant sagitta method[5] and found to be $2400 \pm 500\, m_e$. Since there is no visible decay product emerging from the end of the track and since the scattering measurements are not inconsistent with its being due to a proton, we assume that this track was in fact produced by a proton.

The curious thing about this capture star is the fact that, if we analyse it on the assumption that the proton and the π^--meson arise from the decay of a neutral particle, we find that the Q-value is $36 \cdot 7 \pm 0 \cdot 9$ MeV., which is very close to the Q-value $37 \cdot 40 \pm \cdot 27$ MeV. of the Λ° hyperon.[6] (The angle included between the two tracks is 70·8°.) The event could, therefore, be interpreted in two ways:

(*a*) The three observed quantities, namely, the π^--meson range, the proton range and the angle between their trajectories are such that the apparent Q-value happens to come close to the Q-value of Λ° by accident and the event does *not* represent the decay of a Λ°.

(*b*) The event represents the production of a Λ° during the capture of a K^--meson and the Λ° decayed either at the point of creation or within a small distance of the order $\lesssim 1\,\mu$.

Purely on life-time considerations ($\tau_{\Lambda 0} = 3 \cdot 7 \times 10^{-10}$ sec.)[7] the second alternative seems quite unlikely. Still the close coincidence of " Q-values ' seems remarkable.

Evidence for the association of K-mesons and hyperons in production was given in an earlier paper,[4] similar observations were later reported by other workers.[8,9] The close connection which seems to exist was firmly established by the experiments of Fowler *et al.*[10] who used artificially produced π^--mesons traversing a diffusion cloud chamber filled with hydrogen. These results can be represented in the general form:

$$\pi + \mathcal{N} \rightarrow \Lambda + \mathrm{K}, \tag{1}$$

where the symbol $\mathcal{N}$ designates a nucleon. The genoa Group[11] using emulsions and DeStaebler[12] using cloud chamber have shown that charged or neutral hyperons can be associated with the capture of negative K-mesons. The process could perhaps be written:

$$\mathrm{K} + \mathcal{N} \rightarrow \Lambda + \pi, \tag{2}$$

The example obtained by the Genoa group and one of the cases reported by DeStaebler could then be written down as particular cases of eq. (2):

$$\mathrm{K}^- + \mathcal{N}^\circ \rightarrow \Lambda^- + \pi^\circ, \tag{2 a}$$

and

$$\mathrm{K}^- + \mathcal{N}^\circ \rightarrow \Lambda^\circ + \pi^-, \tag{2 b}$$

respectively. Two other events observed by DeStaebler and probably the one reported here are other particular cases of eq. (2), namely:

$$\mathrm{K}^- + \mathcal{N}^+ \rightarrow \Lambda^\circ + \pi^\circ, \tag{2 c}$$

(Energy and momentum distribution of the visible fragments in our event are consistent with this scheme.)

IV. ACKNOWLEDGEMENT

We are deeply indebted to Professor B. Peters for valuable discussions and keen interest in this work.

We would like to express our thanks to Miss Purohit who discovered the K^--event.

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