OBSERVATIONS ON τ-MESONS AND ON K-MESONS GIVING RISE TO CAPTURE STARS

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Abstract

In an emulsion block detector[1] exposed in the stratosphere three cases of the production of τ-mesons in nuclear disintegrations have been observed and 5 cases of negative K-mesons which when brought to rest are captured by nuclei. In one case the production of a τ-meson is associated with the production of a charged hyperon in the same nuclear event. In another case the production of a negative K-meson is associated with the production of a slow positive K-meson. The production ratio of slow τ-mesons to slow positive π-mesons $\tau/\pi^+ = 1 \cdot 1 + 0 \cdot 8\%$ and the ratio of slow negative K-mesons to slow negative π-mesons $K^-/\pi^- = 0 \cdot 95 \pm 0 \cdot 5\%$. The mass of the τ-meson is found to be

$$M\tau = 975 \cdot 9 \pm 2 \cdot 2 \; m_e$$

and that of K^--mesons

$$M_{K^-} = 927 \pm 75 \; m_e$$

Proof is given that all three of the decay products of the τ-mesons are π-mesons. It is suggested that all τ-mesons observed to decay in emulsions are positively charged and that the K^--mesons observed by us may be the negative counterpart of this particle. Possible relations between the various phenomenologically distinguished types of charged K-mesons are discussed.

I. Experimental Procedure

The work reported in this paper was carried out with an emulsion block detector whose construction has already been described in detail.[1] The block consisted of 24 sheets of 600 μ Ilford G-5 emulsions with lateral dimensions $4'' \times 6''$. It was exposed in a balloon flight at geomagnetic latitude $19°$ for $6\frac{1}{2}$ hours. The balloons spent $4\frac{3}{4}$ hours between 70,000 and 90,000 feet. Tracks of particles which traversed the detector during the balloon exposure could be traced from emulsion to emulsion. Tracks of particles which traversed the stack before the balloon flight (old tracks) could not in general be traced because the relative position of the emulsion sheets was altered just before exposure in the stratosphere. A sample survey showed that a total of 4,800 positive and negative π-mesons came to rest in the stack of which 3,700 were produced in the stratosphere and 1,100 during the air transport of the emulsions from England to India.

We have selected for investigation a random sample consisting of 352 π-μ-e decays and 421 capture stars produced by slow mesons. Amongst the last mentioned events, we found four cases of heavy mesons coming to rest and producing nuclear distintegrations at the end of their range (K^--mesons). The remaining capture stars were produced by π^--mesons, while the π-μ-e events of the first group must be attributed to π^+-mesons.

The tracks of the π^+ and π^--mesons were traced from their end point backwards towards their origin. Some proved to be "old tracks" and could, therefore, not be traced, others were found to enter the stack from the outside and were presumably produced in the packing material. Some could not be traced completely due to faults in the emulsions or other reasons. Many were found to originate in some nuclear disintegration. A few originated in 2 prong stars some of which could be interpreted as the decay of neutral hyperons. Two positive mesons originated in the decay of τ-mesons.

The detailed information on the origin of the 773 slow π-mesons is given in Table I.

TABLE I

	π^+ – mesons	π^- – mesons
Old tracks ..	84	97
Not traced beyond 1–2 cm. of range ..	75	61
Entered from outside ..	109	109
Originated in stars > 2 prongs ..	80	146
Originated in 2 prong stars ..	2	8
From τ – mesons ..	2	0
Total ..	352	421

The two τ-mesons as well as a third τ-meson discovered at random could in turn be traced to their origin in nuclear events. All of their decay products could also be traced for appreciable distances into the emulsion block, some of them to the end of their range.

Of the four K^--mesons found by the investigation of capture stars one was produced before balloon exposure and could, therefore, not be traced to its origin. Two were found to originate in nuclear explosions and one entered the block from the outside. A fifth K^{-}-meson was found by tracing the grey and black prongs of a star which was already known to emit a positive K-meson.

II. MEASUREMENTS ON THE τ-MESONS AND THEIR DECAY PRODUCTS

Brown, Camerini, Fowler, Muirhead, Powell and Ritson[2] who discovered the first τ-meson suggested the decay scheme $\tau \rightarrow 3\pi$. Recently Amaldi *et al.*[3] reviewed the evidence for the nature of the decay particles based on a total of 11 τ-decays which had been observed until then. Although only three of their 33 decay products came to the end of their range in the emulsion and could definitely be identified as π-mesons, the evidence from grain density *versus* scattering on the tracks of the other decay products and the consistency of the Q-values obtained for the reaction assuming the proposed decay scheme, made it highly probable that as originally suggested all these decay products are π rather than μ-mesons and no additional neutral particles are involved.

The much more favourable observational conditions which exist in an emulsion block detector compared to single emulsions permit in our case to exclude the presence of neutral particles in the decay by a more rigorous test on the coplanarity of the charged decay particles. One can also show that in one of our cases in which two of the decay products come to rest in the block and can be identified as π-mesons, the evidence is very strong that also the third decay particle is a π rather than a μ-meson. The originally proposed decay scheme seems, therefore, very firmly established.

Apart from measurements on the track of the τ-meson itself (which will, however, give a mass and Q-value of very limited precision) one can measure the three momenta of the decay particles and the three angles between their tracks. Once the decay scheme is assumed, a Q-value can be calculated from one of the momentum values and any two of the remaining five measurable quantities. It is, therefore, possible to obtain for a given τ-decay a series of Q-values obtained from different sets of the measurable quantities and to obtain a check on the accuracy of measurement from the internal consistency of the results.

From such internal consistency checks it became soon apparent, that in order to measure the Q-value to an accuracy of the order of 1 M*e*V, the customary procedure for measuring angles and particle ranges in emulsions had to be greatly refined, by taking into account the variation in thickness of individual emulsion sheets and the effect of distortion on the angle between steeply dipping tracks. It seemed also desirable to determine directly the stopping power of the particular emulsions used in order to avoid errors due to the variable moisture content of emulsions.

These refinements will eventually also play a role in determining accurate Q-values for the decay of other *K*-mesons and Hyperons, and, are therefore, described in some detail.

(*a*) *The Measurement of Particle Ranges*

The determination of particle range depends on an accurate knowledge of the shrinkage factor, and, therefore, on the emulsion thickness before processing for all emulsion sheets traversed by the track. The conversion of particale range into energy requires an accurate knowledge of the stopping power of the emulsion.

(1) *Stopping Power of the Emulsion Sheets.*—Since unbacked emulsion sheets are free to expand and contract laterally after manufacture it is possible that their stopping power at exposure slightly differs from that normally observed for glass backed emulsions. We found in fact, that the density of two control sheets is about 2% higher than that given by the manufacturer for G-5 plates.

We have, therefore, determined the range of μ-mesons emitted from π-mesons in a direction nearly parallel to the emulsion surface. Our mean value on 18 tracks is $R_{\mu} = 589\,\mu$. Since according to Fry and White[4] the μ-mesons have a 5% straggling in range our value should be accurate to about 1%. We have normalised the range-energy curves for emulsions as given by Beiser[12] to agree with the observed range for μ-mesons.

(2) *Variations in Emulsion Thickness.*—It is apparent from the manufacturing process used by Ilford Limited, where liquid emulsion is poured on a thick, carefully levelled sheet of plate glass, that individual emulsion sheets must be extremely uniform in thickness. Thus it is not necessary to consider thickness variation in a particular emulsion, but variations between different emulsion sheets must be taken into account.

The determination of the unprocessed emulsion thickness can, therefore, be divided into two parts:

(α) Determination of relative thickness of different emulsions.

(β) Determination of the average thickness of the emulsions forming the emulsion block detector.

(α) We select a number of tracks due to energetic heavy primary nuclei which traverse the block in different areas of the plates and with different orientations. We measure for each track in each emulsion (i) the projected track length L_i and determine the average projected track length in the n emulsions:

$$\bar{L} = \frac{\Sigma L_i}{n}$$

The fractional variation of projected track length $\frac{\bar{L} - L_i}{\bar{L}} = \frac{\delta L_i}{\bar{L}}$ varies from emulsion to emulsion. The average variation is 4·6% but occasional values up to 10% do occur.

For the track of a high energy particle whose scattering is negligible, the projected length in two emulsions can differ either because the emulsions had unequal thickness or because of distortion (which moves the exit point on the air surface from its proper position) or because there were small air gaps between emulsions which permitted buckling such that the sheets at exposure were not exactly parallel.

Experimentally we found that except for tracks near the edge of the plates the quantity $\frac{\delta L_i}{\bar{L}}$ was for a given i (*i.e.*, for the same emulsion) nearly equal for all tracks. The main fluctuation of projected length was, therefore, due to variation in emulsion thickness, since buckling should have different effects on tracks in different areas of the plate and the effect of distortion on its projected length should depend both on the location of the track in the plate and on its orientation. From these measurements we obtained for each emulsion sheet its thickness (within 1%) in terms of the average thickness of the sheets.

(β) In order to determine the average thickness of the emulsion before exposure we measured the range of steeply dipping μ-mesons ejected from π-mesons. Taking into account the percentage variation in the thickness of individual emulsion sheets, this average range is nearly proportional to the average emulsion thickness. We find that the emulsion thickness at exposure is very nearly equal to 600 μ as specified by the manufacturer.

With this information on the thickness of individual emulsion sheets we can determine the range of stopping particles to about 1% accuracy corresponding to an uncertainty in energy of about 0·5%. Further uncertainty in the energy arises from possible errors in the deduced stopping power (0·5%) and from straggling which for π-mesons in the energy interval 15–35 MeV amounts to about 2%.

(b) Measurement of Angles between Trajectories

The angle measured between two tracks in a processed emulsion can differ from the angle between the trajectories responsible for the tracks for the following reasons:

(α) The emulsion has shrunk during processing in the direction perpendicular to the emulsion surface (Z-direction).

(β) The emulsion layers may during processing have moved with respect to each other (distortion). Unless the intersecting tracks are parallel to the emulsion surface, distortion will change the angle between tracks.

(γ) Coulomb scattering introduces an uncertainty in the true angle of intersection. Fortunately this does not affect the Q-values appreciably because if the track is due to a particle of high momentum the scattering is small and if it is due to a particle of low momentum the Q-value is insensitive to the angle between this track and those of the other decay products.

In order to measure the angle between two *tracks*, we have to measure the difference of x, y and z co-ordinates between the intersection of the tracks and another point P on each of the two tracks. This point must be chosen sufficiently far from the intersection to permit the accurate alignment of a hairline with the intervening grains of the track. If we want to measure, however, the angle between the *trajectories* of the particles producing the tracks, we must first correct the z co-ordinates of the points P for shrinkage and their x and y co-ordinates for the displacements caused by distortion.

Since we have determined the thickness of each emulsion sheet before exposure, the shrinkage factor involves simply a measurement of thickness of the processed emulsion sheet. This thickness, however, changes with the moisture content of the atmosphere and should, therefore, be redetermined for each angular measurement.*

We now consider the distortion correction to be made for the x and y co-ordinates of P. Let us assume that during the development stage and before the emulsion has hardened a uniform pressure is exerted on a surface perpendicular to the plane of the emulsion (y, z-plane) and let us assume that in this state the emulsion represents a homogenous and elastic solid. The emulsion material will then suffer a displacement S in the x-direction which (because one surface of the emulsion is firmly attached to a rigid glass plate)

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* A. J. Oliver Radiation Laboratory Report U.C.R.L. 2176. April 1953.

will vary along the Z-direction. It is then easily shown that $\frac{\partial^2 S}{\partial Z^2}$ is equal to a constant ($= -$ K), and for the boundary condition where one emulsion surface is rigidly fixed while the other is free to move.

$$S = \left(-\frac{K}{2} Z^2 + KZ_0 Z \right)$$

$$= S_0 \left[2\frac{Z}{Z_0} - \left(\frac{Z}{Z_0}\right)^2 \right] \tag{1}$$

where Z_0 is the emulsion thikness and S_0 is the maximum value of S which occurs on the air surface. Thus, the various grains along a track will be displaced in the x, y plane by an amount which increases first rapidly then slower as one goes from the glass surface ($Z = 0$) to the air surface ($Z = Z_0$). The result is a C-shaped distortion of tracks, the curvature being largest near the glass surface. This is in fact the shape which is generally observed for tracks of fast particles traversing distorted emulsions. The projected shape of the track does not change when the thickness of the emulsion shrinks. The distortion in a certain region of the developed emulsion is defined by the magnitude of the displacement on the air surface $S_0 = \frac{K}{2} Z_0^2$ and the quantity $C = \frac{K}{2} = \frac{S_0}{Z_0^2}$ is a measure of distortion in covans if the surface displacement S_0 is expressed in microns and the emulsion thickness Z_0 in millimeters. Since in this type of distortion $\left(\frac{\delta S}{\delta Z}\right)_{Z=Z_0} = 0$ the projected track retains its true direction near the air surface. Consequently the component of the displacement vector $\vec{S}$ perpendicular to the projection of a given track can be obtained by measuring the distance of the point where the track enters the glass surface to the line which is tangent to the projected track at the air surface. The true vector $\vec{S}$ is determined by making such measurements in the same region of the emulsion on tracks of different orientation.

The x and y co-ordinates of the points P_1 and P_2 on the tracks 1 and 2 whose angle of intersection is to be measured must, therefore, be corrected for distortion in the following way:

(*a*) The vector $\vec{S}$ is determined from the apparent curvature of high energy tracks in the same region of the plate.

(β) The Z co-ordinate (Z_1) of point P and of the intersection point (Z') are measured and expressed as fractions of the emulsion thickness Z_0. The point P_1' which is to be used for the angular measurement is found by moving from P_1 in the direction of the displacement vector $\vec{S}$ by an amount obtained from equation 1:

$$S(Z_1) - S(Z') = S_0\left[\frac{2(Z_1 - Z')}{Z_0} - \frac{(Z_1^2 - Z'^2)}{Z_0^2}\right].$$

In our emulsions where the maximum displacement vector $\vec{S}_0$ is sometimes as large as 40 μ (corresponding to 110 covans) the distortion correction may amount to several degrees for steep tracks both when measuring the projected angle between tracks and when measuring dip angles.

If the decay occurs near one of the emulsion surfaces and one of the fragments is steep and leaves the surface giving a segment of very short length, the measurement of the dip and projected angles can sometimes be carried out more accurately in the adjacent emulsion which is completely traversed by the fragment.

It should be remarked that distortion in the emulsion does not in first order affect the coplanarity of the tracks made by the three decay products of the τ-mesons. The fact that the measured angles between the three tracks add up to 360° is, therefore, no indication that distortion corrections can be neglected.

(c) *Mass Measurements on τ-Mesons*

The result on the measurements of the 3 τ-mesons are given in Table V. In each case unfortunately, the plane of decay makes a large angle with the plane of the emulsion. The manner by which the Q-values were obtained and the errors were estimated is given below:

(α) τ No. 1. The momenta p_1 and p_2 of the stopping π-mesons were obtained from their range. In addition the dip angle of each track and the projected angle between tracks were measured. The decay occurred in a plane which made an angle of 77° with the emulsion surface. The measured deviation from coplanarity was 0·35°.

By using various sets of the measured angles and momenta we can calculate the remaining momenta, the energy of each decay product and the Q-value. Table II shows the results obtained; the measured quantities are indicated at the top of each column. (γ designates the angle between

p_1 and p_2, etc.). Energies and momenta in Table II are expressed in units of the π-meson rest mass ($c = 1$).

TABLE II

τ No. 1

	$p_1p_2\ \alpha$	$p_1p_2\ \beta$	$p_1p_2\ \gamma$	$p_1\ \alpha\beta$	$p_2\ \alpha\beta$
p_1	·641	·641	·641	·641	·625
p_2	·500	·500	·500	·513	·500
p_3	·7445	·715	·735	·7410	·722
E_1	·188	·188	·188	·188	·179
E_2	·118	·118	·118	·124	·118
E_3	·2465	·2295	·241	·245	·233
Q	·5525	·5355	·547	·557	·530

The variation in Q-values is partly due to uncertainty in angular measurements, but primarily it reflects errors due to straggling since we have used in its calculation the energy derived from the range of particles 1 and 2 and of each one separately. That straggling is the largest contribution to the uncertainty of the Q-values is indicated by the fact that both in case of τ No. 1 and τ No. 2 (Table III) the extreme Q-value occur if we rely in the calculation on the range of only one or the other of the two stopping π-mesons.

We, therefore, take the average of the various Q-values and assign as probable error a value covering the entire spread of values obtained:

$$Q_1 = \cdot 543 \pm \cdot 014\, m_\pi c^2$$

The track of the third meson which escapes, has near the decay point a grain density of $53\cdot 5 \pm 2\cdot 5/100\,\mu$ while the grain density expected for a π-meson of momentum calculated in Table III should be $53\cdot 7 \pm 0\cdot 7/100\,\mu$. If on the other hand the excaping particle were a μ-meson its grain density should be $39\cdot 0/100\,\mu$ in disagreement with the observed value. Thus, it seems certain that all three decay products are π-mesons.

τ No. 2. One positive and one negative π-meson come to rest in the block. The plane of decay makes an angle of 85° with the plane of the emulsion. The measured deviation from coplanarity is 0·3°. The Q-values determined by using various sets of measured quantities are given in Table III.

TABLE III

τ No. 2

	$p_1p_2\ \alpha$	$p_1p_2\ \beta$	$p_1p_2\ \gamma$	$p_1\ \alpha\beta$	$p_2\ \alpha\beta$
p_1	·581	·581	·581	·581	·566
p_2	·482	·482	·482	·491	·482
p_3	·790	·773	·784	·789	·770
E_1	·1565	·1565	·1565	·1565	·149
E_2	·110	·110	·110	·114	·110
E_3	·274	·264	·270	·274	·262
Q	·5405	·5305	·5365	·5445	·521

$$Q_2 = 0\cdot533 \pm \cdot012\, m_\pi c^2$$

τ No. 3. The plane of decay makes an angle of 75° with the emulsion surface. The measured deviation from coplanarity is 1·6°. In this case only one (positive) π-meson comes to rest in the block, the others escape. The stopping π-meson (π_1) carries only 9% of the available energy. This makes it difficult to obtain good measurements:

(1) The strong scattering of π_1 introduces an uncertainty in the angle between π_1 and π_2 and between π_1 and π_3. This probably accounts for the measured lack of coplanarity.

(2) The Q-value becomes extremely sensitive to the angle between the energetic mesons π_2 and π_3 which travel very steeply in nearly opposite direction.

The most accurate Q-values are obtained in this case by determining the momentum of π_2 from grain density *versus* range in the 16 emulsions which this particle traverses before escaping and using p_1, p_2 and either of the angles between π_1 and the other mesons.

The results are given in Table IV. In addition to the error due to the angular measurements which is responsible for the difference in Q-values in the two columns, we have to make allowance for an additional 2% error arising from the uncertainty in the energy determination of π_2.

TABLE IV

τ No. 3

	$p_1p_2\ \beta$	$p_1p_2\ \gamma$
p_1	·310	·310
p_2	·7905	·7905
p_3	·672	·6965
E_1	·047	·047
E_2	·275	·275
E_3	·2045	·219
Q	·5265	·541

$$Q_3 = \cdot 534 \pm \cdot 017\ m_\pi c^2$$

The weighted average for these three τ-mesons ($m_\pi c^2 = 141 \cdot 1$ (MeV) is

$$Q_\tau = 75 \cdot 6 \pm 1 \cdot 1 \text{ MeV}$$

$$M_\tau = (3 \cdot 536 \pm 0 \cdot 008)\ m_\pi c^2 = 975 \cdot 9 \pm 2 \cdot 2\ m_e{}^*$$

TABLE V

Parent Particle					Decay Products			
No.	Origin	Range (cm.)	Energy MeV	Q-value (MeV.)	No.	Sign of Charge	Energy MeV	Angles
1	21+2α	0·0367	6·4	76·7±2·0	1	+	26·2	∢ 2·3 = α = 121·85°
					2	+	16·8	∢ 3·1 = β = 137·2°
					3	(−)	33·7	∢ 1·2 = γ = 100·8°
2	6+0p	0·665	31·7	75·3±1·7	1	+	21·8	α = 132·9°
					2	−	15·6	β = 141·6°
					3	(?)	37·9	γ = 85·5°
3	13+10α	0·747	33·6	75·3±2·4	1	+	6·6	α = 161·8°
					2	?	38·8	β = 79·3°
					3	?	29·9	γ = 118·8°

* Recent determinations by Smith *et al.* [11] show that the mass of the π-meson should be reduced to $m_\pi c^2 = 139 \cdot 5$ Mev. Using this mass would reduce the Q value by $\frac{1}{2}\%$ and lead to a mass $M^\tau = 966 \pm 2 \cdot 2\ m_e$.

In addition to the statistical error, this Q-value may be in error by somewhat less than 1 MeV due to uncertainty in the range energy relation.

Our value is in good agreement with the value $Q_\tau = 76 \cdot 3 \pm 1 \cdot 7$ derived by Amaldi, *et al.*[3] based on the average of 11 τ-mesons observed in emulsions by various laboratories. It is somewhat higher than the value reported by one of us at the Cosmic Ray Conference at Bagnéres de Bigorre in July 1953, a value which had been obtained without corrections for distortions and for variations in emulsion thickness.

III. The Charge of τ-Mesons

τ No. 1 can be definitely identified as positive because two of its decay products undergo π-μ-e decay. A similar event was recently observed at Bristol.† Among the 15 τ-mesons observed so far in emulsions there are, therefore, 3 cases, where the charge of two of the decay products was identified ($5\,\pi^+$ and $1\,\pi^-$) and 4 cases in which the charge of one decay product was identified ($3\,\pi^+$ and $1\,\pi^-$). The probability of obtaining 8 or more positive π-mesons among 10 identified decay products under these conditions is $3 \cdot 5\%$ if they are obtained from a sample which consist of equal numbers of positive and negative τ-mesons. The probability is, however, 7 times as high if the sample consists of positive τ-mesons only. While it cannot as yet be ruled out, therefore, that some of the τ-mesons observed to decay in emulsions are negatively charged it is more likely that all are positive.

On the other hand from the report of Leighton at the Cosmic Ray Conference in Bagnéres it appears that at least one of the three τ-mesons whose decay in the gas of the cloud chamber was observed by him was negatively charged. It seems, therefore, reasonable to assume that both positive and negative τ-mesons are produced but that in the dense material of the emulsion the negative ones are absorbed by nuclei before decay.

IV. K^--Mesons

We have already mentioned that among 421 capture stars investigated in our emulsion block we found 4 examples where the incident slow meson was heavier than a π-meson. A fifth example of this type of event was found by following tracks from a star among whose fragments was a previously identified positive K-meson (emitting a relativistic singly charged decay particle at the end of its range.) The particles producing these capture stars are certainly negatively charged and have a mass intermediate between π-mesons and protons. They are, therefore, designated as K^-particles.

† D. H. Perkins (Priv. Comm.)

The relevant data on these events are given in Table VI, most of these data have already been given in our preliminary report.[5] Details on the

TABLE VI

Negative K-Mesons

No.	Origin	Range	Mass (m_e)	Range total (t) or observed (o)	Mass (m_e)	Energy (MeV)	Remarks	Energy Release excluding Neutral Fragments
1	$14+2n$	308 μ	1000^{+720}_{-400}	15·8 μ (t)		1·0	Probably proton	185 MeV
				5·7 μ (t)		0·5	Probably proton	
				0·39 cm.(o)	290^{+80}_{-50}	28·1 ± ·8	π-meson	
2	$25+5n$	92 μ	?	48 μ (t)		2·2	Probably proton	199 MeV
				5·5 μ (t)		0·5	Probably proton	
				139 μ (t)		4·2	Probably proton	
				0·354 cm. (o)	200^{+60}_{-30}	29·2±0·9	This particle is a π-meson since it produces a nuclear interaction in flight after traversing 3·5 mm. of path	
3	$4+6n$	2·5 cm.	1015±120	385 μ (t)		7·8	Probably proton	>246 MeV
				46 μ (t)		2·1	Probably proton	
				140 μ (t)		4·1	Probably proton	
				0·14 cm. (o)		> 17 MeV	Proton or deuteron	
				1·76 cm. (o)	1836	>180 MeV	Proton	
4	Outside of block	2·926 cm.	850±95	407 μ (t)		8·1	Probably proton	31 MeV
				456 μ (t)		9·0	Probably proton	
	Old Track 5	1·2mm.	540^{+290}_{-170}	282 μ (t)		6·5	Probably proton	>140 MeV
				295 μ (o)		>120 MeV	Probably proton	

mass measurements for those K^--mesons for which sufficient track length is available have been given in an earlier paper.[6] Our best mass value is

$$M_{K^-} = 927 \pm 75\, m_e$$

Event No. 1 can be attributed to the capture of a K^--meson because a L-meson (presumably a 28 MeV π-meson) is emitted from the capture star and the particle which produces the star can be identified as singly charged with a mass which is probably lower than that of a proton but higher than that of a π-meson.

Event No. 2 is very similar to event No. 1, but here the track of the particle responsible for the capture star is so short (92 μ) that the only information on the particle producing the capture star is that it has a mass larger than the π-meson and carries a charge Z less than 3. An Alternative interpretation along the line of Danysz and Pniewski[7] is, therefore, possible in this case: the event may be the emission of a helium fragment incorporating a hyperon which subsequently decays and breaks up the nucleus. The measured energy of the emitted π-meson would not be inconsistent with such an interpretation.

In Event No. 3 the K^--meson is identified both by direct mass measurement and by the fact that the observable energy release in the capture star exceeds the rest energy of a π-meson.

In Event No. 4 the identification of the K^--mesons rests only on measurements of its mass.

Event No. 5. This is an "old event" in which the track of the K^--mesons cannot be traced. The mass value is, therefore, rather inaccurate because the available track length is small. The mass seems to lie higher than the π-meson mass. The observable energy release in the capture star lies close to but does not clearly exceed the rest energy of a π-meson. It is, therefore, highly probable but not quite conclusive that this event should be attributed to a capture of a K^-meson at rest.

V. The Frequency of Production of Slow τ and K^-Mesons

Although our statistics are still very poor, we can at least make a rough estimate of the frequency of production of τ and K^--mesons.

Excluding "old tracks" we have in a particular area located and traced towards their origin 268 positive and 324 negative π-mesons (see Table I). 56% and 42% respectively originated outside the emulsion block. If we apply the same percentages to the tracks which have been followed only through part of their range in the block we find 117 out of 268 π^+-mesons and 189 out of 324 π^--mesons are created in the block, and give rise to decays or capture stars after coming to rest. If n designates the number of particles satisfying these criteria we have in a given area

$$\frac{n_{\pi^+}}{n_{\pi^-}} = \frac{117}{189} = \cdot 62$$

We now assume that all τ-mesons decaying in emulsion are positive and, therefore, give rise to $2\pi^+$ and $1\pi^-$-mesons. In our 3 cases we found that 5 of the 9 decay products came to rest in the block ($1\cdot 7$ π-mesons per τ-meson). In view of the dimensions of our block and the most probable range of 1 cm. for the decay products it seems reasonable to accept this number as the average number of stopping π's per τ-decay.

Let n_τ be the number of τ-mesons created and decaying in the block. They will give rise to $\frac{2}{3}\times 1\cdot 7\, n_\tau$ positive and to $\frac{1}{3}\times 1\cdot 7\, n$ negative π-mesons stopping in the block. The fraction of stopping π^+ which have their origin in τ-decays is, therefore, $1\cdot 13 \dfrac{n_\tau}{n_{\pi^+}}$.

The ratio of π^--mesons which have their origin in τ decays and which come to rest *and produce capture stars* to the total number of such mesons is $\dfrac{1}{3} \times 1\cdot 7 \times 0\cdot 73 \times \dfrac{n_\tau}{n_{\pi^-}} = \cdot 256 \dfrac{n_\tau}{n_{\pi^+}}$. (The factor $0\cdot 73$ arises from the fact that 27% of π^- mesons fail to produce visible capture stars).

Since we have found 2 τ mesons by tracing $117\,\pi^+$ from their decay and $189\pi^-$ from their capture stars towards their origin we find

$$\frac{n_\tau}{n_{\pi^+}} = \frac{2}{1\cdot 13\times 117 + 0\cdot 256\times 189} = (1\cdot 1 \pm 0\cdot 8)\%$$

For the ratio of κ^--mesons to π^--mesons which come to rest in the block and produce capture stars we obtain

$$\frac{n_{K^-}}{n_{\pi^-}} = \frac{4}{421} = (0\cdot 95 \pm 0\cdot 50)\%$$ if we include all observations,

$$\frac{n_{K^-}}{n_{\pi^-}} = \frac{3}{324} = (0\cdot 93 \pm 0\cdot 55)\%$$ if we omit "old tracks",

and $$\frac{n_{K^-}}{n_{\pi^-}} = \frac{2}{189} = (1\cdot 05 \pm 0\cdot 75)\%$$ if we confine ourselves to particles originating inside the emulsion block detector.

VI. On the Nature of Charged *K*-Mesons

The relations which exist among the various phenomena which involve the disintegration or nuclear capture of charged *K*-mesons are still far from clear and the remarks in this section which owe a great deal to the discussions at the Cosmic Ray Conference at Bagnéres in July 1953 are, therefore, largely speculative.

In the Cloud Chamber observations we have three types of events:

(1) Particles which are either positive or negative and disintegrate in flight into 3 L-mesons.

(2) Particles which are either positive or negative and decay in flight into a single charged L-meson (V-events).

(3) Particles which when brought to rest in an absorber inside the cloud chamber disintegrate and give rise to a single L-meson (and sometimes a γ-ray going in the opposite direction). The sign of charge of these particle (giving rise to the so-called S-events) is known only in the four cases observed by the Pic du Midi group of the Ecole Polytechnique and was positive in each of the four cases.

The type No. 2 is about 20 times as frequent as type No. 1.

In nuclear emulsions one has also observed three types of events.

(4) Particles which disintegrate at rest into 3 π-mesons.

(5) Particles which give rise to capture stars when brought to rest.

(6) Particles which decay at rest into a single charged L-meson. In at least two cases the L-meson is not relativistic and can be identified as a μ-meson. In the other cases the L-mesons are relativistic though not monoenergetic and cannot definitely be identified as π or μ.

(The possible division of this group into Kappa-mesons giving rise to μ-mesons of varying energies and χ-mesons giving rise to π-mesons of a unique energy cannot as yet be considered to be established beyond doubt).

Types No. 4 and No. 5 seem to occur with about equal frequency as we have shown in the preceeding section. In scanning emulsions in various laboratories type No. 6 has been found about 9 times as frequently as type No. 4. Since decay event No. 4 is much easier to observe than the event No. 6 it seems that type No. 6 is at least 10 times, possibly as much as 20 times more frequent than type No. 4.

It seems quite certain that events No. 1 observed in cloud chambers are related to the τ-meson (event No. 4) observed in emulsions. In a previous section we have shown that very probably all τ-mesons observed in emulsion are positive. Therefore, we may identify the *positively* charged particles decaying into 3 L-mesons in the gas of the cloud chamber with the τ-meson. We believe that the *negatively* charged particles decaying into 3 L-mesons in the gas of the cloud chamber should be identified with event No. 5, *i.e.*, the negative K-mesons giving rise to capture stars at rest. The arguments in favour of this identification are:

(α) τ^+-mesons and K^--mesons have within rather narrow limits the same rest mass.

(β) τ^+-mesons and K^-mesons have lifetime sufficiently long to be brought to rest in solid matter.

(γ) τ^+-mesons and K^--mesons of low energy are produced with comparable frequency.

It seems fairly certain that the S-events in cloud chambers (event No. 3) should be identified with the S-events in emulsions (event No. 6) and that the particles giving rise to these events are included among those giving rise to the V-events (group No. 2). The evidence of the Paris group on the charge of S-particles would indicate that the S-events in cloud chambers and emulsions should be identified only with the *positively* charged particles giving rise to the V-events although this evidence rests on only four charge determinations.

If we admit all these suggested identifications it follows that the *negatively* charged particles which give rise to V-events have not been observed when at rest either in cloud chambers or in photographic emulsions. It is hard to believe that they could have escaped detection in photographic emulsions unless they simply come to rest without producing any capture star. We must then assume that this particle is captured by a nucleus, but that in spite of the resultant release of half a BeV of energy no visible prongs are emitted in at least 80% of the cases. Or we may assume that the negative particle giving rise to V-events has a much shorter lifetime than its positive counterpart and hardly ever comes to rest in emulsions. (Cloud Chamber evidence on the lifetime of charged V's does not however, support this conclusion.)

If in order to escape from the conclusion that this negative particle is captured without producing a capture star, we discount the as yet incomplete evidence of the Paris group in favour of the exclusively positive charge of particles giving rise to S-events, we must assume alternatively that at least 80% of these particles do not interact with nuclei when at rest, but decay even in the presence of fairly heavy nuclei.

These conclusions are not appreciably modified if we assume that part or even all of the observed capture stars produced by negative *K*-mesons should be attributed not to negative τ-mesons but to the negative primaries of V-events brought to rest. The frequency of occurrence of such capture stars as measured by us is too low, being comparable to the frequency of τ-decays rather than to the 20 times more abundant number of S-events in emulsions. This is supported by the evidence of Harris and Friedlander[8] who failed to find any clear cases of K^--capture in a large sample of stars induced by slow particles (σ-stars).

Nevertheless this alternative is worth considering because it offers the possibility for a certain simplification. In a recent paper[6] we have pointed out that the masses of τ-mesons, K^--mesons giving rise to capture stars and at least the majority of particles giving rise to S-events are equal within rather narrow limits. The approximate equality of the relative frequency of S-events to τ-decays in emulsions and of V-events to τ-decays in cloud chambers indicates that also the lifetimes of these particles are similar. The available observations are, therefore, consistent with the view that there exists only one type of charged *K*-particle which can decay either into a single L-meson plus some neutral particles or into 3 π-mesons, the former mode of decay being more probable by a factor of the order of 20. We have then to assume that the negative particle when brought to rest in heavy material gives rise to capture stars in about 5% of the cases and gives no visible star in the remaining cases. The observed equality in the number of τ-decays and of capture stars produced by *K*-mesons must then be considered to be accidental. If we make this assumption then it follows that the negative particles which fail to produce visible capture stars are nevertheless captured by nuclei and do not decay; otherwise we could not account for the preponderance of positive π-mesons among the disintegration products of the τ-decay occurring at rest.

Thus if we are dealing with only one type of charged *K*-mesons, the negative particle when brought to rest in emulsion is captured but rarely produces a visible capture star. If we consider the τ-particle to be of different nature and we are dealing, therefore, with more than one type of charged *K*-particle then the negative particle responsible for V-events in cloud chambers either is captured when at rest in nuclear emulsions without normally producing visible capture stars or it is a non-interacting particle which decays into one L-meson even if brought to rest.

A decision between the last mentioned alternatives could in principle be derived from observations of the interaction mean free path of shower particles in high energy jets, which according to Daniel, *et al.*[9] contain $23 \pm 10\%$ of K-mesons. In view of the existing cloud chamber evidence only a small percentage should be τ-mesons. The mean-free path for nuclear interaction in emulsion of shower particles from jets of more than 50 BeV energy has been studied in Bristol and in our laboratory. We have observed so far 22 interactions‡ in an integrated path length of 532 cm. while the Bristol group[9, 10] has reported 9 interactions in 239 cm. path in emulsion. This gives a mean free path for shower particles from high energy jets of $24 \cdot 9 \pm 4 \cdot 5$ cm. compared to the geometric mean free path of $24 \cdot 2$ cm. This result seems to indicate geometric interaction cross-section also for K-mesons but is within statistical error still consistent with a mixture consisting of π-mesons and about 10% protons with geometric cross-section and not more than $17 \cdot 5\%$ K-mesons with zero cross-section. This latter alternative also implies that the ratio of neutral π-mesons to shower particles in high energy jets should be larger than $0 \cdot 35$, if we assume that the production ratio $\pi^{\circ}/(\pi^{+} + \pi^{-})$ is always equal to one half. Neither the mean-free path of shower particles nor the ratio of π°-mesons to shower particles is as yet known with sufficient accuracy to decide whether the majority of K-mesons are interacting or non-interacting particles.

We believe then that this evidence and that of the Paris group on the charge of S-particles, while not conclusive, favours the view that negative particles of mass $\sim 1000\, m_e$ which when decaying in flight emit a single charged L-meson, are captured by nuclei when brought to rest in emulsions but do not in the majority of cases give rise to visible capture stars.

If subsequent cloud chamber experiments should confirm that S-events are always produced by positively charged particles or if mass measurements on particles coming to rest in emulsion selected without bias as to their possible decay should prove the existence of K-particles which neither decay nor give capture stars, these conclusions would be greatly strengthened. If on the other hand cloud chamber experiments gave positive and negative S-particles in comparable number or in emulsion work particles of mass $\sim 1000\, m_e$ selected without bias were found to decay in the large majority of cases, the particle responsible for charged V-events are very probably

‡ We are indebted to Mr. Rama of this laboratory for permission to quote some of his unpublished results.

non-interacting. The observed mean free-path of shower particles would then give an upper limit to their production frequency. Furthermore, in this case the K^--particles observed by us must be of a different type and their identification with negative τ-mesons would seem more compelling.

In conclusion we would like to emphasize again two observations which may or may not be relevant to the question of the production of K-particles:

Among 9 nuclear events which give rise to charged K-mesons we found:

One event in which a τ-meson is emitted together with a charged hyperon which decays in flight into a L-meson and one or more neutral particles. (If there is only one neutral particle its rest mass must exceed 1570 m_e) and one event in which a K^--meson is emitted which gives rise to a capture star together with a K-meson which gives rise to an S-event.

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