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W A COOPER, H FILTHUTH,
J A NEWTH and R A SALMERON
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Further Measurements on Charged V-Events.

W A COOPER, H FILTHUTH, J A NEWTH and R A SALMERON (*)

CERN Geneva

(ricevuto il 23 Maggio 1956)

Summary — The decays of 150 charged V particles from lead and copper have been observed in a magnetic cloud chamber. Among the slow charged V events, which are all interpreted as K mesons, the proportions of the different decay modes are in good agreement with the results given by nuclear emulsions. Our own evidence agrees with that of other experiments which suggests that an appreciable fraction of the charged V events with high energy (> 1 GeV) are due to the decays of hyperons. Data on the positive to negative ratio of slow K mesons are discussed and a partial explanation in terms of the energy dependence of the production cross section is suggested. Among the 150 events, 3 are most easily interpreted as the decays of K_S^0 mesons and 1 as the decay of a Σ^+ particle. In addition 10 events are interpreted as the decays of τ mesons, of which 1 is negative.

1 — Introduction

In 1954, the Jungfraujoch cloud chamber group published a paper (BUCHANAN *et al* ⁽¹⁾) giving full measurements of 44 charged V-events observed in a magnet cloud chamber at an altitude of 3580 m. At that time there was little statistical information available about charged V-events and the interpretation of the measurements was limited by their inaccuracy and by the smallness of the sample of events.

Since the earlier paper was written, a great deal of information has been published by groups working on cosmic-ray V-particles. In addition, there

(*) On leave of absence during part of the work from the Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

⁽¹⁾ J S BUCHANAN, W A COOPER, D D MILLAR and J A NEWTH: *Phil Mag*, 45, 1025 (1954)

are now available many measurements of heavy mesons and hyperons observed in large blocks of photographic emulsion exposed at great altitude. Finally, studies of heavy mesons produced by large accelerators are now appearing and many very precise measurements have been made on these particles. The following decay modes are now established:

(1)	$K_{\mu 2} \rightarrow \mu + \nu$	$(p^* = 238 \text{ MeV/c})$
(2)	$K_{\pi 2} \rightarrow \pi + \pi^0$	$(p^* = 205 \text{ MeV/c})$
(3)	$K_{\mu 3} \rightarrow \mu + \pi^0 + ?$	$(p^* \leq 218 \text{ MeV/c})$
(4)	$K_{\beta} \rightarrow e + ? + ?$	$(p^* \leq 246 \text{ MeV/c})$
(5)	$\tau' \rightarrow \pi + 2\pi^0$	$(p^* \leq 133 \text{ MeV/c})$
(6)	$\tau \rightarrow 3\pi$	$(p^* \leq 125 \text{ MeV/c})$
(7)	$\Sigma \rightarrow \pi + \text{Nucleon}$	$(p^* \sim 190 \text{ MeV/c})$
(8)	$\Xi^- \rightarrow \pi^- + \Lambda^0$	$(p^* \sim 120 \text{ MeV/c})$

The values of the momentum of the secondary in the centre of mass system are given in brackets.

In this paper we summarize the information we have obtained from a total of 150 charged V -events observed at the Jungfraujoch (including those reported by BUCHANAN *et al*). We compare our results with those of other groups in an attempt to determine any residual points of disagreement. For brevity, we refer below to the paper of BUCHANAN *et al* as paper I.

2 – Corrections to Earlier Measurements

In paper I there were some errors that must be corrected. The first of these concerns the event RP 993, a positive K -meson apparently having a mass greater than $1100 m_e$. All the measurements on this event have recently been repeated and an arithmetic error in calculating the line of flight of the secondary particle has been found. As a consequence, the angle of decay is 107° and not 117° as originally stated, and the momentum of the secondary is 230 MeV/c and not 250 MeV/c .

These alterations make a significant change in the interpretation of the event. The mass of the primary particle, on the assumption that there is a single neutral secondary of zero rest mass is now found to be

$$\begin{aligned} &(1100 \pm 55) m_e \text{ if the charged secondary is a } \mu\text{-meson, or} \\ &(1060 \pm 60) m_e \text{ if the charged secondary is an electron} \end{aligned}$$

Although the quoted errors are greater than standard deviations (as described in Table III of paper I) it is clear that the mass values are not incompatible with $965 m_e$. We conclude, therefore, that the event is not convincing evidence for a K-meson with mass greater than $965 m_e$.

The remaining errors are of less importance. The event QR 979 of paper I has been excluded from the present analysis since the intersection of the two tracks in this event occurs too near to the back of the illuminated volume of the cloud chamber for us to be certain that the tracks do not cross or originate from a nuclear interaction in the gas. Event RE 410 was listed as positive whereas it is, in fact, negative.

In addition, because of the importance of the positive excess among the V-particles, we have, in this paper, used a more stringent criterion for determining the signs of fast particles. Applying this criterion to the earlier events we find that five V^+ -events and one V^- -event should now be classed as of indeterminate sign. Making these corrections the numbers of positive, negative and indeterminate events in paper I are 23:12:8 rather than 29:13:2.

3 – General Survey of the Events

Of the total of 150 charged V-events, 43 were reported in I and the remainder have been observed in the period up to October, 1955. The apparatus ⁽²⁾ has not been altered significantly. The total number of photographs taken is about 100 000. Of these, 35 000 were taken with a 13 mm copper plate across the centre of the cloud chamber and 10 000 with a 30 mm lead plate in the same position. Nineteen charged V-particles came from nuclear interactions in these two plates.

In addition to the 150 charged V-events, 10 events have been observed that are best interpreted as the decays of τ -mesons into three charged π -mesons. The numbers of positive and negative V-particles and τ -mesons are given in Table I.

One criterion for identifying a charged V-event has been made less strict than that used in paper I. The value of the transverse momentum ($P_2 \sin \varphi$) of the secondary particle has been required to be greater than 50 MeV/c by at least one standard deviation. Previously a value of 100 MeV/c was required. Relaxing this criterion may allow a large-angle scatter of a fast particle by an argon nucleus to be misinterpreted as a V-event but the total number of such scatters expected in our experiment is about two.

It has been emphasized by the Ecole Polytechnique workers ⁽³⁾ that the

⁽²⁾ J A NEWTH: *Suppl Nuovo Cimento*, **11**, 297 (1954)

⁽³⁾ R ARMENTEROS, A ASTIER, C D'ANDLAU, B GREGORY, A HENDEI, F MULLER, C PEYROU and R RAU: *Pisa Conference, mimeographed report* (1955)

TABLE I – *Sign distribution of charged V particles observed in the Jungfraujoch cloud chamber*

Group of events	Positive	Negative	Doubtful sign	Total
Reported in Paper I (*)	23	12	8	43
Since Paper I	46	32	29	107
Total	69	44	37	150 (+)
$\tau \rightarrow 3\pi$	7	1	2	10
Charged V's produced in copper or lead plate	6	7	6	19

(*) See corrections in Sect 2
 (+) The total of 150 charged V particles includes the 19 produced in the plate

sample of V-events identified with a magnet cloud chamber is limited by the cloud chamber performance in a very definite manner. In particular, the identification of small angle decays depends directly upon the maximum detectable momentum in the chamber. If the decay angle (φ) is small the condition $P_2 \sin \varphi > 50 \text{ MeV}/c$ can only be satisfied when the lower limit for P_2 is high. The result of this restriction is a strong bias against recognizing decays in which the angle is below some value characteristic of the apparatus. For our equipment we find empirically that very few events with φ less than 10° have been identified. This is shown by the histogram of decay angles given in Fig 1.

Fig 1 – Histogram of decay angles for all the charged V events observed in the Jungfraujoch cloud chamber

The full significance of this limitation is seen when our events are compared with those reported by ARMENTEROS *et al* ⁽³⁾. The median decay angle for our 69 positive events is 37° and for the 44 negative events it is 25° . The Ecole Polytechnique group found values of 18° for 54 positive events and 12° for 44 negative events. This difference is discussed fully when our results are compared with those of other groups.

4 – Dynamics of the Decays

4.1 Direct Mass Estimates — Of the 150 primary particles 20 had measurable momenta below 350 MeV/c and the masses of the particles could be estimated from the density of ionization in their tracks. For all 20 particles (14 positive and 6 negative) the estimated mass is consistent with a unique value near to $1000 m_e$. In addition, for 16 particles (12 positive and 4 negative) the upper limit to the estimate of mass is less than $2000 m_e$; these particles cannot, therefore be hyperons.

Nearly all the secondary particles could be light mesons but only three can be so identified from momentum and ionization. Three of the secondary particles are probably *not* light mesons; the events are discussed below.

In event SE 234 the secondary particle has a momentum of (460^{+130}_{-90}) MeV/c and its ionization is estimated to be between $2I_0$ and $3I_0$. Its mass is therefore between $1400 m_e$ and $2200 m_e$. This particle traverses the 13 mm copper plate in the cloud chamber and its momentum loss in the plate and its ionization below the plate are both compatible with the behaviour of a proton. The primary particle in this event has a track length of only 4 cm in the chamber and its momentum cannot be found. The angle of decay is 15° . It seems most reasonable to suggest that this event is a hyperon decay of the type

$$\Sigma^+ \rightarrow P + \pi^0 + 110 \text{ MeV}$$

If this is correct the primary particle had a time of flight in the chamber of $1.5 \cdot 10^{-10}$ s.

In two events the secondary particles are apparently *lighter* than π^- or μ mesons. SD 1472 is a photograph of poor contrast but the secondary momentum is only 30 MeV/c and a μ -meson of this momentum would have an ionization of $7.5 I_0$. We estimate the ionization from the photograph as $< 3I_0$. The second event is QM 861 which is reproduced in the plate. The relevant measurements are given in Table VI. If we assume that the event is the decay of a K-meson into a μ -meson, the ionization densities of the two tracks should be $2.2 I_0$ for the primary and $2.6 I_0$ for the secondary. From the photograph it appears that the secondary is less heavily ionizing than the primary and its mass should therefore be less than that of a μ -meson.

For neither of these two last events is the interpretation completely certain but, since the K_S mode of decay is established, we much prefer to interpret the decays in this way.

4.2 Transverse Momentum Distribution — In paper I distributions of the transverse momenta of the secondary particles were given in an attempt to

distinguish between 2- and 3-body decay schemes. The results were not significant and we do not consider it worth while to present further distributions of this type. TRILLING and LEIGHTON ⁽⁴⁾ have made a careful study of the experimental bias introduced into such distributions and there is no doubt that the histograms given in Fig. 1 of paper I were more affected by bias than was thought.

4.3 Determination of p^* – Among the 150 events there are 26 where the momenta of both primary and secondary particles can be measured (15 positive and 11 negative). In these cases the secondary momentum (p^*) in the rest-frame of the primary has been calculated by assuming masses for the two particles. Table II lists the results obtained.

Of the 15 positively charged particles there are 11 which give values of p^* such that the decay could be that of a K_{π^2} or K_{μ^2} meson. The mean value of p^* for these 11 events is 203 MeV/c if the secondaries are π -mesons and 202 MeV/c if they are μ -mesons.

The negative particles give 10 such values out of 11 events and we find that the mean value of p^* is 209 MeV/c assuming π -meson secondaries and 194 MeV/c assuming μ -meson secondaries.

The events excluded when finding these mean values of p^* are the following:

- 1) Event QM 861 which is thought to be an example of K_S^+ -decay,
- 2) Two positive events (SN 184 and TF 289) for which the values of p^* are 115^{+18}_{-17} MeV/c and 135^{+18}_{-15} MeV/c,
- 3) The negative event SY 531 with a value of p^* of 109^{+16}_{-10} MeV/c,
- 4) Event RP 993

5 – Mean Lifetime Estimates

As in paper I, we have analyzed the distribution of our events in an attempt to determine the mean lifetime of the primary particles. The momenta of the primary particles were estimated where they could not be measured (see Fig. 2) and, for the purpose of calculation, the particles were all assumed to be K_{π^2} -mesons. The curves for K_{μ^2} -decay differ from these by about 10%. The time (t_i) that each particle spent in the cloud chamber was calculated together with the corresponding « potential » time (T_i) and these times were then

⁽⁴⁾ G. H. TRILLING and R. B. LEIGHTON: *Phys. Rev.* **100**, 1468 (1955).

TABLE II -- *The 26 events observed at the Jungfraujoch which give accurate measurements* p_1 = momentum of primary particle, p_2 = momentum of secondary particle, φ = angle between the directions of primary and secondary, p_π^* = momentum of the secondary particle in the centre of mass system assuming that it is a π meson, p_μ^* = momentum of the secondary particle in the centre of mass system assuming that it is a μ meson, $p_{\pi\max}^*$ is obtained by altering p_1 , p_2 and φ in such a way as to increase p^* as much as possible while remaining compatible with their quoted errors, $p_{\pi\min}^*$ is made as small as possible in a similar way

The events shown are those with $p_{\pi\max}^* - p_{\pi\min}^* < 2.0 \cdot 10^8$ eV/c. The errors in p_1 and p_2 are found from an m.d.m. calculated in the way described in Paper I. The mass $4.93 \cdot 10^8$ eV/c² was assumed for the primary particle in the calculation of p^* .

Event	Sign	p_1 10 ⁸ eV/c	p_2 10 ⁸ eV/c	φ degrees	p_μ^* 10 ⁸ eV/c	p_π^* 10 ⁸ eV/c	$p_{\pi\max}^*$ 10 ⁸ eV/c	$p_{\pi\min}^*$ 10 ⁸ eV/c
QD 138	+	1.9 ± 0.3	2.0 ± 0.3	47 ± 3	1.82	1.80	2.21	1.52
QL 707	+	2.2 $\begin{smallmatrix} +0.6 \\ -0.5 \end{smallmatrix}$	2.7 $\begin{smallmatrix} +0.3 \\ -0.2 \end{smallmatrix}$	32 ± 2	2.08	2.05	2.42	1.70
QM 861	+	3.4 ± 0.3	0.66 ± 0.08	82 ± 2	1.02	1.18	1.28	1.08
RG 585	+	3.9 $\begin{smallmatrix} +2.3 \\ -1.0 \end{smallmatrix}$	1.2 ± 0.2	75 ± 1	1.34	1.42	2.42	1.20
RP 993	+	2.04 ± 0.06	2.3 ± 0.1	107 ± 2	2.80	2.82	2.95	2.71
SC 226	+	2.8 $\begin{smallmatrix} +0.8 \\ -0.5 \end{smallmatrix}$	3.9 ± 0.4	43 ± 2	2.78	2.76	3.15	2.34
SF 1726	+	8.6 $\begin{smallmatrix} +7.0 \\ -3.0 \end{smallmatrix}$	2.7 $\begin{smallmatrix} +0.4 \\ -0.3 \end{smallmatrix}$	35 ± 2	1.62	1.78	3.15	1.38
SN 146	+	2.2 ÷ 3.7	3.2 ± 0.4	33 ± 2	2.17	2.04	2.52	1.65
SN 814	+	2.5 ÷ 4.0	0.9 ± 0.03	73 ± 2	1.04	1.15	1.33	0.98
SQ 387	+	1.7 ÷ 2.2	2.4 $\begin{smallmatrix} +0.2 \\ -0.1 \end{smallmatrix}$	85 ± 2	2.51	2.52	2.78	2.36
SS 242	+	2.0 $\begin{smallmatrix} +0.7 \\ -0.4 \end{smallmatrix}$	2.3 $\begin{smallmatrix} +1.3 \\ -0.6 \end{smallmatrix}$	41 ± 1	1.73	1.70	2.45	1.13
SY 238	+	3.0 $\begin{smallmatrix} +0.6 \\ -0.4 \end{smallmatrix}$	3.7 $\begin{smallmatrix} +1.0 \\ -0.7 \end{smallmatrix}$	23 ± 2	2.19	2.15	2.88	1.54
SZ 984	+	10.0 $\begin{smallmatrix} +4.0 \\ -2.0 \end{smallmatrix}$	2.5 $\begin{smallmatrix} +2.5 \\ -0.8 \end{smallmatrix}$	33 ± 1	1.56	1.72	3.18	1.24
TC 1363	+	3.0 ± 0.2	1.8 ± 0.6	97 ± 2	2.36	2.44	3.20	1.92
TF 289	+	1.9 ÷ 2.7	1.35 ± 0.08	72 ± 1	1.33	1.35	1.53	1.20

TABLE II (continued)

Event	Sign	p_1 10 ⁸ eV/c	p_2 10 ⁸ eV/c	φ degrees	p_μ^* 10 ⁸ eV/c	p_π^* 10 ⁸ eV/c	$p_{\pi\max}^*$ 10 ⁸ eV/c	$p_{\pi\min}^*$ 10 ⁸ eV/c
NJ 93	—	3.5 $\pm$ 0.5	2.8 $\pm$ $^{1.1}_{0.6}$	53 $\pm$ 2	2.24	2.25	2.72	1.76
QG 66	—	3.4 $\pm$ $^{0.6}_{0.5}$	1.6 $\pm$ $^{0.3}_{0.2}$	88 $\pm$ 2	2.05	2.13	2.64	1.79
QH 425	—	7.0 $\pm$ $^{2.0}_{1.5}$	1.4 $\pm$ 0.2	55 $\pm$ 2	1.60	1.81	2.56	1.35
RD 473	—	7.0 $\pm$ 1.0	2.1 $\pm$ 0.4	40 $\pm$ 1	1.45	1.55	2.11	1.21
RQ 461	—	7.5 $\pm$ $^{2.5}_{1.5}$	3.2 $\pm$ 0.3	37 $\pm$ 1	1.98	2.03	2.21	1.85
SD 1314	—	2.4 $\pm$ 0.2	1.9 $\pm$ 0.2	78 $\pm$ 2	1.96	1.99	2.23	1.78
X 38	—	2.5 $\div$ 3.5	3.0 $\pm$ 0.3	47 $\pm$ 3	2.24	2.23	2.51	1.97
SF 223	—	1.5 $\div$ 2.1	1.7 $\pm$ 0.3	124 $\pm$ 3	2.24	2.30	2.80	1.80
SY 531		2.2 $\pm$ $^{0.9}_{0.4}$	0.66 $\pm$ $^{0.20}_{0.10}$	106 $\pm$ 2	0.99	1.09	1.25	0.89
TC 1546	—	2.0 $\div$ 3.0	2.3 $\pm$ 0.2	66 $\pm$ 3	1.21	2.14	2.30	1.88
TC 1700	—	2.0 $\div$ 3.0	2.5 $\pm$ $^{0.3}_{0.2}$	74 $\pm$ 2	2.42	2.43	2.88	2.24

combined by BARTLETT's procedure ⁽⁵⁾ to obtain an estimate of the decay constant ($1/\tau$) of the particles

Because the charged V-events are certainly a mixture of different types of decay we made a large number of different classifications of the events in an attempt to select a group rich in short-lived particles. For every group the mean lifetime was estimated and for nearly every group the value of $1/\tau$ obtained was less than one standard deviation from zero. Some of the results are given in Table III.

Classification 4) in Table III is similar to one used by TRILLING and LEIGHTON ⁽⁴⁾ and shows in the same way that there may be a short-lived component of the V-particles produced in the thin copper plate placed across the chamber. In assessing the significance of our result it should be borne in mind that we made about 20 different classifications of our events. Even if all the particles had a long mean lifetime, we expect to find a value of $1/\tau$ differing from zero by two or more standard deviations in one out of 30 *random* selections.

⁽⁵⁾ M. S. BARTLETT: *Phil. Mag.*, **44**, 249 and 1407 (1953)

Fig 2 - The relation between the momenta of primary and secondary particles^{*} and the decay angle for the $K_{\pi 2}$ meson

TABLE III - *Lifetime Estimates*

In the first three rows the times of flight have been obtained in cases where the primary momentum was unmeasured, by calculation from P_2 and φ assuming the decay of a $K_{\pi 2}$ (see Fig 2). In the last row the decay $\Sigma \rightarrow \pi + \text{neutron}$ has been assumed

Class of particles	Total	Positive	Negative	$1/\tau$ (10^{10} s^{-1})
1 All events, except 3 K_0	147	67	43	-0.003 ± 0.026
2 All events from copper plate	16	6	6	-0.06 ± 0.13
3 Events from copper plate excluding those which cannot be $\Sigma^\pm$	13	4	5	$+0.63 \pm 0.30$
4 As 3 but assuming all events to be $\Sigma^\pm$	13	4	5	$+0.64 \pm 0.29$

The only safe conclusion that can be drawn from this analysis is that a large fraction of the primary particles has a mean lifetime greater than $2 \cdot 10^{-9}$ s. There is an indication of some short-lived particles among the primaries coming from the copper plate but our evidence is far from conclusive.

6 – The Positive Excess

In the past a great deal of apparently conflicting evidence has been published on the relative numbers of V^{+-} and V^{-} -particles. Thanks largely to the work of the Paris group at the Ecole Polytechnique it seems now to be possible to fit all the published information into a relatively simple picture. Briefly, there is a large positive excess for the slow particles that are observed to decay in magnet cloud chambers. Among the high energy particles there is a negative excess. The extent to which this high-energy negative excess is apparent depends upon the performance of the apparatus since the decay angles are generally small in these events.

With our apparatus we find a large positive excess among the primaries with momenta below 600 MeV/c (31 positive and 12 negative). By contrast, at momenta above 1 GeV/c the numbers are 24 positive and 22 negative. In Table IV we compare these figures with those obtained in other experiments. Unfortunately, the intervals of momentum chosen for comparison are not constant but there is clear evidence of agreement in the main features.

It is safe to assume that the decays of slow V-particles are detected with high efficiency in all cloud chamber experiments. These particles can frequently be directly identified as K-mesons (a hyperon with momentum below 800 MeV/c is heavily ionizing) and we can conclude from the results quoted in Table IV that there is a positive excess of about 3.4 to 1 among the observed K-mesons with momenta less than, say, 600 MeV/c. The agreement between different cosmic ray cloud chamber experiments on this point is reasonably good.

Concerning the negative excess at high energies, the situation is less clear. Our own observations are not valuable because we identify so few events with decay angles less than 10° . The obvious explanation in terms of known particles is that Σ^{-} -decays are responsible for this excess. Owing to their short mean lifetime these particles are unlikely to decay inside a cloud chamber unless their momenta are several GeV/c and, at these momenta, a decay of the type $\Sigma^{-} \rightarrow N + \pi^{-} + 118 \text{ MeV}$ has an angle of less than 15° . If this explanation is correct, the negative excess may be partly or wholly an experimental bias since the decay of a Σ^{+} -particle into a proton and a π^0 -meson is extremely difficult to recognize, the angle of decay being only about 2° for a Σ^{+} with a momentum of 5 GeV/c.

We have little to contribute to the study of these fast particles and in the

TABLE IV – *The momentum dependence of the ratio of positive to negative V particles observed in various experiments*

Group	Low momenta			High momenta		
	Class of particles	+	—	Class of particles	+	—
Cal Tech (4)	$V^\pm$ with heavily ionizing primary	19	5	$V^\pm$ with lightly ionizing primary	22	38
Princeton (13)	Measured events (+) $P_1 < 1 \text{ GeV/c}$	15	10	Measured events (+) $P_1 > 1 \text{ GeV/c}$	6	11
École Poly technique (3)	Well measured events $P_1 < 1 \text{ GeV/c}$	20	4			
»	8 events, mean initial $P_1 \sim 0.5 \text{ GeV/c}$	22	2			
»	$\tau \rightarrow 3\pi$ $P_1 < 1 \text{ GeV/c}$	5	2	$\tau \rightarrow 3\pi$ $P_1 > 1 \text{ GeV/c}$	0	2
Jungfraujoch	Measured events (+) $P_1 < 0.6 \text{ GeV/c}$ (*)	31	12	Measured events (+) $P_1 > 1 \text{ GeV/c}$	24	22
»	$\tau \rightarrow 3\pi$ $P_1 < 1 \text{ GeV/c}$	6	0	$\tau \rightarrow 3\pi$ $P_1 > 1 \text{ GeV/c}$	1	1

(+) The primary momentum has in some cases been estimated from a measured secondary momentum and decay angle and the assumption of the $K\pi_2$ decay mode (see Fig. 2)

(*) 6 positive and 2 negative events could be hyperon decays

following sections we restrict our attention to the measurement and interpretation of the K meson decays

7 – The Decay Modes of the Slow Charged V-Particles

It is possible to estimate the relative proportions of the different types of K meson decay using the dynamical measurements reported in Sect. 4. The different modes of decay that have to be considered are (1)–(6) as listed in the introduction.

From magnet cloud chamber measurements it is hardly ever possible to obtain a value of p^* with a precision better than $\pm 10 \text{ MeV/c}$ and the errors are more usually $\pm 30 \text{ MeV/c}$. For this reason the only valuable classification is to make a broad division between those events with p^* near to 200 to 240 MeV/c and those with p^* significantly less than 200 MeV/c . We

class all p^* values where the quoted errors include part of the range from 190 MeV/c to 250 MeV/c as « normal ». Values less than 190 MeV/c by at least one deviation are called « low ». Clearly, the events with normal p^* will include some $K_{\mu 3}$ - and K_{β} -decays but the events with low p^* should *not* include $K_{\mu 2}$ - and $K_{\pi 2}$ -decays.

The numbers of normal and low p^* values from our 26 events were given in Sect. 4. In Table V we compare these with other results obtained from cosmic ray cloud chamber experiments.

From the table it seems that the events with low p^* form about 20% of the total of both positive and negative K-decays. In this 20% may be included some τ' -decays, $K_{\mu 3}$ -decays and K_{β} -decays. The number of τ' -decays can be found from the experimentally determined branching ratio (1:5) between the two modes of decay of positive τ -mesons ⁽⁶⁾.

TABLE V – *Distribution of p^* values from various experiments*

An event with low p^* is taken as one where the quoted range of errors does not include a value > 190 MeV/c. A normal value is taken as one where the quoted range of errors includes a value between 190 MeV/c and 250 MeV/c. The nature of the secondary particle assumed in calculating p^* is shown in brackets.

Group	Positive				Negative			
	Total	Normal	Low	Unweight ed mean p^* (10^8 eV/c)	Total	Normal	Low	Unweight ed mean p^* (10^8 eV/c)
Cal Tech ⁽⁴⁾	18	18	1	2.37 (π) 2.31 (μ)	6	6	0	2.06 (π) 2.00 (μ)
Princeton ⁽¹³⁾	13	9 (*)	2	2.13 (π)	10	7 (*)	1	2.31 (π)
École Poly technique ⁽³⁾	14	8	6	2.10 (π) (μ)	8	5	3	2.56 (π) (μ)
Jungfraujoch	15	11 (+)	3	2.02 (π) 2.03 (μ)	11	10	1	2.09 (π) 1.94 (μ)
Total	61	46	12	—	35	28	5	—

(*) 2 events which may be due to hyperons are omitted
(+) RP 993 is omitted

⁽⁶⁾ J. CRUSSARD, V. FOUCHÉ, J. HENNESSY, G. KAYAS, L. LEPRINCE RINGUET, D. MORELLET and F. RENARD: *Nuovo Cimento*, **3**, 731 (1956)

If we normalize to a total of 100 K-meson and τ -meson decays we now have the following estimate of their composition:

	positive	negative
« Normal » p^* events	70	79
Low p^* events other than τ'	13	12
$\tau \rightarrow 3\pi$ decays	14	7
τ' decays	3	2

The errors in these estimates are large and there is certainly no significant difference between the proportions for the positive and negative events

It is only possible to proceed further with the analysis by making some assumption about the distribution of p^* values in the $K_{\mu 3}$ and K_{β} decay modes. Because of the inaccuracy of the measurements it is likely that the only values of p^* that are classified as « low » are values below 150 MeV/c (*). We may assume that about half the $K_{\mu 3}$ - and K_{β} -decays have p^* below 150 MeV/c and half above (?). This estimate is not unreasonable and the result of our analysis would not be changed greatly unless the proportion of decays with low p^* were, in fact, as low as one quarter. There is a bias favouring the inclusion of events with low p^* in our sample due to the requirement that the event should be well measured. The École Polytechnique group estimates (3) that a low value of p^* is, *a priori*, twice as likely to be selected as a normal value. Taking this estimate and again normalizing to a total of 100 mesons we find the following figures for their composition:

	positive	negative
$K_{\mu 2}$ and $K_{\pi 2}$	63	71
$K_{\mu 3}$ and K_{β}	20	20
τ	14	7
τ'	3	2

From the information we have discussed here a further separation of the first two classes is not possible

(*) The criteria for recognizing a charged V event may prevent values of p^* less than 50 MeV/c from being recorded but, for the slow primary particles we consider, this effect is unlikely to be important as the V events can frequently be identified without reference to the absolute value of the transverse momentum

(?) C M YORK: *Phil Mag*, **43**, 985 (1952)

The K_β mode of decay – While we cannot deduce any reliable figure for the ratio of the numbers of $K_{\mu 3}$ and K_β -decays among the events there is some interest in recording the details of 3 events that are probably K_β -decays. Event QM 861 (Plate 1) is identified from the momentum and ionization of the secondary particle and has been discussed in Sect. 4. Event SD 1472 is also identified in this way but the photograph of this event is of poor quality. The third event (SO 333) is a negative V-event where only a lower limit can be set to the primary momentum. However, this sets a lower limit also to

TABLE VI – K_β Events

The p^* is calculated assuming $M_1 = 493 \text{ MeV}/c^2$ $M_2 = 0.51 \text{ MeV}/c^2$

θ^* is the angle of emission of the secondary in the centre of mass system with respect to the direction of the primary in the laboratory system. The value $\theta^* = 175^\circ$ for event SO 333 is found assuming $p_1 = 10 \cdot 10^8 \text{ eV}/c$. p_1 , p_2 and φ are defined in the legend to Table II.

Event	Sign	P_1 ($10^8 \text{ eV}/c$)	P_2 ($10^8 \text{ eV}/c$)	φ Degrees	p^* ($10^8 \text{ eV}/c$)	θ^* Degrees
QM 861	+	3.5 ± 0.3	0.67 ± 0.06	82 ± 2	75 ± 9	112
SD 1472	+	$7.3^{+6.0}_{-2.3}$	0.3 ± 0.1	117 ± 5	73^{+90}_{-36}	158
SO 333	—	> 10	0.60 ± 0.02	163 ± 3	> 244	175

the value of p^* . If the secondary is a μ meson this lower limit is $370 \text{ MeV}/c$, a value incompatible with the decay of any known particle. If the secondary is an electron the value of p^* is $> 244 \text{ MeV}/c$.

The details of the 3 presumed K_β -events are given in Table VI. In all three events the secondary was emitted backwards in the centre of mass system nearly along the primary line of flight. This is effectively a prerequisite for identifying a K_β -decay in flight. To our knowledge, no other examples of K_β -decay have been observed in cloud chamber experiments and we must regard our three events as a statistical fluctuation on a smaller expected number.

8 – Comparison with other Experiments

8.1 Relative abundances of the modes of decay – The figures given in Sect. 7 for the composition of the K-decays can be compared with the results obtained in several experiments using photographic emulsions. In Table VII this comparison is made.

Plate 1 A K meson (travelling horizontally) decays into a particle which is probably lighter than a μ meson

The emulsion experiments are able to resolve the p^* distribution of the secondaries with far greater precision than is possible in the experiments we have so far considered. The value of the comparison made in Table VII is

TABLE VII — *The relative frequencies of K decay modes found in various experiments*

	Emulsion evidence			Cloud chamber evidence	
	École Poly technique ⁽⁶⁾	K beam RITSON <i>et al</i> ⁽⁸⁾	« G » Stack ⁽⁹⁾	Positive	Negative
$K_{\mu 2}$	54	57	61	63	71
$K_{\pi 2}$	26	31	18		
$K_{\mu 3}$	4	1	3	20	20
K_{β}	8	2	8		
τ	7	7	8	14	7
τ'	1	2	2	3	2

that it suggests good agreement between all the observations made on the relative frequencies of the different K-decays.

In emulsions K^- decays are not observed when the K-particles come to rest and no information is available on the different modes of K^- -decay other than that summarized in Sect 7. It is possible that the K^- -meson decay modes are the same and have the same proportions as those of the K^+ -meson but there is some evidence against this simple view. This point is discussed further in § 3 i) below.

§ 2 The ratio of positive to negative K-mesons — The positive excess of 3.4:1 that was found in Sect 6 is much less than the 10:1 found by the Padua group in the G-stack cosmic ray experiment ^(9,10). However, GEORGE *et al* ⁽¹²⁾ find that 29% of the negative K-mesons which they observed stopping in

⁽⁸⁾ D. M. RITSON, A. PEVSNER, S. C. FUNG, M. WIDGOFF, G. T. ZORN, S. GOLD HABER and G. GOLDHABER: *Phys Rev*, **101**, 1085 (1956)

⁽⁹⁾ G. STACK COLLABORATION: *Nuovo Cimento*, **2**, 1063 (1955)

⁽¹⁰⁾ M. CECCARELLI, M. GRILLI, M. MERLIN, G. SALANDIN, and B. SECHI: *Pisa Conference, mimeographed report* (1955)

⁽¹¹⁾ M. SCHEIN, D. M. HASKIN and R. G. GLASSER: *Nuovo Cimento*, **3**, 131 (1956)

⁽¹²⁾ E. P. GEORGE, A. J. HERZ, J. H. NOON and N. SOLNISEFF: *Nuovo Cimento*, **3**, 94 (1956)

emulsion placed in the K-meson beam from the Bevatron gave no star at the end of their track. Correcting the G-stack data for this loss would reduce their ratio from 10:1 to 7:1 but this is still incompatible with the mean value of 3.4:1 for events in cloud chambers. It is almost impossible to imagine how the cloud chamber result could be biased. Because the altitude at which the G-stack was exposed (27 km) is much greater than that at which the cloud chamber experiments were performed (3 km) the incident flux of particles is different in composition and mean energy in the two cases. This may well have caused a larger proportion of positive K-mesons to have been produced in the G-stack. The lower energies of the K-mesons observed in the G-stack may also affect, indirectly, the positive excess.

All the cosmic ray experiments find a much lower positive to negative ratio than that of 100:1 found in the K-meson beam produced by protons of 6 GeV incident on a copper target ⁽¹³⁾. A ratio of 100:1 is also found when the protons produce K-mesons directly in photographic emulsions ⁽⁶⁾. CECCARELLI *et al* ⁽¹⁰⁾ after considering several possibilities explained the very high positive excess in the machine data by assuming a shorter lifetime for the majority of the negative K-particles. It now seems, however ⁽¹⁴⁾, that if there is a difference between the lifetimes of the K^+ and K^- -mesons, it is insufficient to explain this effect. The next simplest explanation seems to be that depending on the different effective energies in the cosmic ray experiments and the machine experiments.

The production processes allowed by the scheme of Gell-Mann and Pais ⁽¹⁵⁾ and Nakano and Nishijima ⁽¹⁶⁾ are:

(1)	$\pi^- + N \rightarrow Y^{+0} + K^{+0}$	(0.75 GeV)
(2)	$N + N \rightarrow N + Y^{+0} + K^{+0}$	(1.57 GeV)
(3)	$\pi^- + N \rightarrow N + K^{+0} + \bar{K}^{+0}$	(1.34 GeV)
(4)	$N + N \rightarrow N + N + K^{+0} + \bar{K}^{+0}$	(2.48 GeV)

The threshold energies in the laboratory system are given in brackets. Considering these reactions, we suggest that at higher energies the reactions (3) and (4) are more important than (1) and (2), whereas at lower energies such

⁽¹³⁾ W. W. CHUIP, S. GOLDHABER, G. GOLDHABER, W. R. JOHNSON and F. WEBB: *Pisa Conference, mimeographed report* (1955)

⁽¹⁴⁾ E. L. ILOFF, G. GOLDHABER, S. GOLDHABER, J. E. LANUTTI, F. C. GILBERT, C. E. VIOLET, R. S. WHITE, D. M. FOURNET, A. PEVSNER, D. RITSON and M. WIDGOLF: *UCRL*, 3323 (1956)

⁽¹⁵⁾ M. GELL-MANN and A. PAIS: *Glasgow Conference*, p. 342 (1954)

⁽¹⁶⁾ K. NISHIJIMA and T. NAKANO: *Prog. Theor. Phys.*, **10**, 581 (1953)

as given by 6.2 GeV protons, (2) is more important than (4). This involves a rather rapid increase with energy of the cross-sections for (3) and (4). If these cross-sections increase more rapidly than the cosmic ray spectrum falls, so that high energy interactions are important, the cosmic ray cloud chamber results can clearly be explained, since any positive to negative ratio greater than 1 can be obtained by a suitable combination of the processes (1) to (4).

8.3 Further Comparison — In the above comparisons we have made some effort to emphasize the general agreement which exists between the experiments. There remain difficulties in some details.

i) If the positive excess is 3.4:1 the Ecole Polytechnique group should have observed 6 negative S-events while they have only found 2. Either this is a statistical fluctuation, in which case there is no evidence for the $K_{\mu 2}$ being only positive; or the $K_{\mu 2}$ is really only positive and the charged V-particles contain a component with a smaller positive excess than the S-particles.

ii) It is seen in Table V that the Ecole Polytechnique has an abnormally large fraction of events with low p^* . The effect seems too large to be due to better momentum resolution.

iii) The change of the positive to negative ratio with the energy of the charged V itself was explained in Sect. 6 by supposing an admixture of hyperons. However, the τ -mesons, which cannot be confused with hyperons, seem to show the same behaviour (see Table IV). If the K-mesons produced in high energy interactions have, themselves, high energies then an increase in the cross-section of processes (3) and (4) could cause a decrease in the positive excess though not a negative excess. Perhaps one observes a combination of both effects.

iv) ARNOLD *et al.*⁽¹⁷⁾ have found a short lifetime for a class of particles which are not hyperons. The classes were highly selected and therefore small and none of the lifetimes differs from infinity by as much as two standard deviations. Bearing in mind the difficulty (and sometimes the impossibility) of the correction procedure in such classes, the short lifetimes may not be significant.

v) In contrast to the results obtained with 6.2 GeV protons (which give 2 GeV available energy in the centre of mass system) SCHEIN *et al.*⁽⁹⁾ find no positive excess for K-mesons produced by 4.6 GeV π^- -mesons (which give 2.2 GeV available energy in the centre of mass system) though the statistical significance is not discussed. His result may show that reaction (3) is already important at 2.2 GeV in the centre of mass system.

⁽¹⁷⁾ W. H. ARNOLD, J. BALLAM and G. T. REYNOLDS: *Phys. Rev.*, **100**, 295 (1955).

9 – Interactions which Produce Charged V-Events

We have found 19 V-particles which were clearly produced in the copper or lead plate. Table VIII summarizes the essential data on these events. It is noticeable that the number of heavy prongs of the interaction is always small, but this may be because some are stopped in the plate. Events SN 814 and SY 873 may represent large angle scattering of K-mesons with, in the case of SN 814, a charge exchange process. In the case of SS 678 a particle is scattered 8° in the plate and below it decays as a V^- -particle. The other features of the events are apparent from the table and it does not seem valuable at this stage to attempt any more elaborate discussion of them. In particular some of the V-particles are probably hyperons, so that the momentum spectrum, if evaluated, would be difficult to interpret.

TABLE VIII – *Interactions producing charged V particles inside the cloud chamber in copper and lead plates*

N_h = number of heavily ionizing particles observed coming from the nuclear interaction
 N_s = number of lightly ionizing particles observed coming from the nuclear interaction

Event	Sign of V	Sign of primary	N_h	N_s	Event	Sign of V	Sign of primary	N_h	N_s
SI 496	+	0	4	6	ST 223 +	—	0	0	0
SN 814	+	0	0	0	SY 868	—	$\pm$	0	2
SO 1073	+	?	2	1	TH 759	—	$\pm$	0	2
SY 873	+	$\pm$	0	0	JB 127	—	?	0	1
SY 1058	+	?	2	4	JK 23	$\pm$	—	0	1
TJ 199	+	0	0	(15) *	QU 372	$\pm$	0	1	0
JB 127	—	?	0	1	SG 182	$\pm$	$\pm$	1	1
SG 35	—	$\pm$	3	2	X 43	$\pm$	?	1	1
SL 424	—	$\pm$	0	1	SJ 928	$\pm$	$\pm$	0	2
SL 990	—	$\pm$	0	(12) *	SS 678 $\times$	—	$\pm$	0	0

(*) Most of these particles are electrons

(+) There may be secondary particles outside the illuminated volume

($\times$) See text

10 — Conclusions

We have attempted to combine our measurements of slow K-meson decays with others made in similar experiments and conclude that:

1) The positive excess of slow K-mesons (momentum < 600 MeV/c) observed under heavy material exposed to cosmic radiation is about 3.4:1 in cloud chamber experiments

2) Our 150 events are only sufficient to give a lower limit ($2 \cdot 10^{-9}$ s) to the lifetime of charged V-particles

3) About 20% of the K-mesons have values of p^* significantly less than 200 MeV/c

4) The relative frequencies of the different decay modes, so far as they can be separated, can be the same for both K^- and K^+ -mesons and the mean relative frequencies are

$K_{\mu 2}, K_{\pi 2}$	$K_{\mu 3}, K_{\beta}$	τ	τ'
67	20	10	3

These ratios are in good agreement with all the emulsion experiments made on positive K-mesons (both from machines and from cosmic radiation) Three events have been observed which are most easily interpreted as the decays of K_{β} -mesons One of these is negatively charged

5) It seems possible to account for all K-meson observations using only one mean lifetime (10^{-8} s) for both positive and negative particles In this case we are led to suppose that the cross sections of the reactions

vary differently with energy such that reactions (1) and (2) predominate at low energies, but at energies of several GeV, (3) and (4) become rather rapidly more important Such a scheme would account for the observed values of the positive to negative ratio except for the difference between that observed in the G-stack and the mean value found in cosmic ray cloud chamber experiments

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RIASSUNTO (*)

Si riportano i dati su 150 V cariche, generate in piombo e rame, osservate in camera a nebbia con campo magnetico. Le V cariche di bassa energia, interpretate tutte come mesoni K , mostrano una ripartizione nei differenti modi di decadimento che si accorda bene con i risultati forniti dalle osservazioni in emulsioni nucleari. Sono state trovate indicazioni di decadimenti iperonici nelle V cariche di alta energia (> 1 GeV) ed in quelle prodotte in rame. Si discute il rapporto tra il numero di K negativi e quello dei K positivi di bassa energia; viene suggerita una interpretazione in funzione di una dipendenza dall'energia della sezione d'urto per produzione. L'interpretazione più probabile di 3 dei 150 eventi è quella di mesoni K_S^0 , mentre altri 10 eventi sono interpretabili come decadimenti di mesoni τ , di cui uno negativo.

(*) Traduzione a cura della Redazione

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