these appeared nearer 5 mb/sterad. The proper correction is not completely clear since two independent absolute calibrations of the β counters were made at Rochester.[8]

No correction has been made to the earlier Harwell data[9] since the beam was independently calibrated. More recent data give a somewhat lower differential cross section,[10] also an independent measurement of the total cross section would give a decreased differential cross section.[11]

A similar correction would also lower the earlier Harvard results,[12] to 4.3 mb at 105 Mev and 5.3 mb at 75 Mev. The extrapolation to these energies of the $C^{12}(p,pn)C^{11}$ cross section seems somewhat uncertain, however. We have therefore not made the correction at this time. The present measurements do not involve this uncertainty, and the absolute cross sections obtained in this experiment should be more reliable. A smooth connection can now be made between the data near 30 Mev[4,13–15] to the energy-independent behavior between 120 Mev and 400 Mev.[2,5,6,9–11,16–19]

ACKNOWLEDGMENTS

It is a pleasure to thank the many members of the cyclotron laboratory who contributed to this experiment. In particular, the assistance of R. Chrenko, A. Erwin, F. Fishman, R. Fullwood, J. LaTourrette, L. Paabus, J. Schwartz, and S. Shapiro was greatly appreciated. The advice of Dr. R. H. Stahl and Dr. C. A. Swenson on the use of liquid helium and hydrogen is gratefully acknowledged.

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[9] Cassels, Pickavance, and Stafford, Proc. Roy. Soc. (London) **214**, 262 (1952).
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[13] J. L. Yntema and M. G. White, Phys. Rev. **95**, 1226 (1954).
[14] Bruce Cork, Phys. Rev. **80**, 321 (1950).
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[16] Chamberlain, Pettengill, Segrè, and Wiegand, Phys. Rev. **93**, 1424 (1954).
[17] Chamberlain, Pettengill, Segrè, and Wiegand, Phys. Rev. **95**, 1348 (1954).
[18] D. Fischer and G. Goldhaber, Phys. Rev. **95**, 1350 (1954).
[19] Marshall, Marshall, and Nedzel, Phys. Rev. **92**, 834 (1953); Phys. Rev. **93**, 927 (1954); Marshall, Marshall, and de Carvalho, Phys. Rev. **93**, 1431 (1954).

PHYSICAL REVIEW VOLUME 101, NUMBER 3 FEBRUARY 1, 1956

Characteristics of K^+-Particles*†

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(Received October 21, 1955)

A large nuclear emulsion stack was exposed in the magnetically analyzed beam of K^+ particles, at the Berkeley Bevatron. The secondaries of stopped K-mesons have been analyzed, and examples of all the known modes of decay: $K_{\mu 2}$, $K_{\pi 2}$, K_{e3}, $K_{\mu 3}$, τ, and τ' have been identified. The decay processes of the $K_{\mu 2}$, $K_{\pi 2}$, and τ' mesons have been confirmed, and a possible decay scheme for the $K_{\mu 3}$ has been considered. The masses of the particles decaying in the different ways have been determined from momentum-range measurements, and for $K_{\mu 2}$ and $K_{\pi 2}$ particles, from the Q of the decay as well. The masses of all the particles are consistent with a value of 965 m_e, within about 10 m_e. The relative frequencies of the various modes of decay have been estimated, and by comparison with other data, it is found that the apparent lifetimes of all the particles are $\sim 1\times 10^{-8}$ sec.

INTRODUCTION

Since the discovery of heavy mesons, a considerable amount of information has been collected on their decay products, masses, and lifetimes. Among positive particles there have been phenomenologically identified six types of heavy mesons, and these have been named the τ, the $K_{\pi 3}$ or τ', the $K_{\mu 3}$, the K_{e3}, the $K_{\pi 2}$, and the $K_{\mu 2}$, each characterized by a particular decay mode. Experimental evidence thus far presented indicates a mass of ~ 1000 m_e for all particles, and lifetimes varying from 10^{-8} to 10^{-10} sec.[1]

These particles, together with all heavy unstable

* The work at Massachusetts Institute of Technology and at Harvard University was supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
† The work at Brookhaven National Laboratory and at the University of California was carried on under the auspices of the U. S. Atomic Energy Commission.

[1] For summaries of data, see *Proceedings of the Fifth Annual Rochester Conference on High-Energy Physics* (Interscience Publishers, Inc., New York, 1955), and Dilworth, Occhialini, and Scarsi, Ann. Rev. of Nuc. Sci. **4**, (1955).

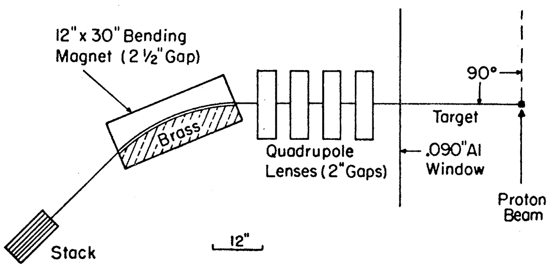

FIG. 1. Experimental arrangement of the strong-focusing channel used in the exposure.

particles, have also come to be systematized in various schemes, in which K-particles are treated as bosons and are assigned particular values of a new quantum number (e.g., the "strangeness").[2] Theoretical arguments have been proposed to account for the various known characteristics. These have led to certain proposals, and an important one, one that has not as yet been completely tested, deals with τ and θ ($K_{\pi 2}$) particles and maintains, on grounds of spin and parity, that these particles are not identical[3,4] and that perhaps some measurable difference distinguishes them. In addition to the prediction of two groups of particles, there is a possibility of the existence of a fermion, an example of which could be the $K_{\mu 3}$.

At the 1955 Conference in Rochester, it was evident that the situation was neither clear nor were all the answers easily forthcoming through cosmic radiation investigations.

Shortly after this meeting, a new magnetically analyzed beam (the so-called K-particle beam) was realized at the Bevatron in Berkeley.[5] This offered a unique possibility of approaching again the problems associated with the K-meson under entirely different conditions, and through this means to search out a more complete and accurate picture for positive K-particles. The details of such an investigation will now be discussed.[6]

EXPERIMENTAL PROCEDURE

In order to differentiate among the several decay modes of K-particles, a pellicle stack of rather large dimensions was employed. It was composed of 100 pellicles of Ilford G5 emulsion, each 400μ thick, with lateral dimensions of $10\frac{1}{4}$ in.$\times$16 in.

The plates were exposed in a beam of magnetically analyzed and focused secondary particles emanating from a small tantalum target ($\frac{1}{2}$ in.$\times\frac{1}{4}$ in.$\times\frac{1}{4}$ in.) which was bombarded by $\sim 4\times 10^{12}$ protons at an energy of 6.2 Bev. The average momentum to which the stack was exposed was 330 Mev/c, but varied from 316 to 340 Mev/c over the stack. The experimental arrangement at the Bevatron was that recently reported by Kerth *et al.*[5] and is shown diagramatically in Fig. 1.

As indicated in Fig. 1, the stack was exposed with its leading edge $\sim$3 meters from the target. For K-particles of momentum 300 Mev/c, this corresponds to a proper time of flight before entering the emulsion block of 1.5×10^{-8} sec. (As is evident, there is a strong bias in this experiment against the detection of K-particles having mean lives $<2\times 10^{-9}$ sec.)

TECHNICAL DETAILS

Prior to its exposure, the stack was prepared by photographically printing on each pellicle a grid of lines forming 1-mm squares, each of which contained index numbers. The position of the grid on each plate was very accurately determined relative to holes punched in the emulsion for use in aligning the stack. On those plates where the grid was easily visible, the following of a track from one emulsion to another was greatly facilitated. The technique used was that recently described by Goldhaber *et al.*[7] In addition, thin x-ray lines were made on the edges of the stack prior to exposure to be used in aligning the stack after processing.

Following the exposure, the stack was carefully weighed and its accurate dimensions were determined. From these data, the average density was calculated to be (3.85 ± 0.02) g/cm^3, with an estimated variation in parts of the stack of ± 0.04 g/cm^3.

The mounting of the emulsions on Ilford treated glass backings and the processing were then carried out using standard techniques. The processed plates were cut so as to leave a $\frac{3}{8}$-in. glass border around the emulsion. A number of brass tabs were cemented to this glass border to form a "standard edge" accurately placed relative to the x-ray alignment markings.[7] This was done by using a jig with microscopes of 60$\times$ magnification to view the x-ray lines, with final adjustments made by shimming or filing the tabs. The alignment of adjacent plates was accurate to $\sim$50μ, and this accuracy was found to exist over most of the area of the $10\frac{1}{4}$ in.$\times$16 in. plates during the analysis of K-secondaries.

In order to be able to handle such large plates in scanning, microscope stages were modified. This was

[2] M. Gell-Mann and A. Pais, *Proceedings of the Fifth Annual Rochester Conference on High-Energy Physics* (Interscience Publishers, Inc., New York, 1955), p. 131; R. G. Sachs, Phys. Rev. **99**, 1573 (1955); M. Goldhaber, Phys. Rev. **101**, 433 (1956).

[3] The spin and parity of the τ, as pointed out by Dalitz,[4] may be determined from observations on the energy and angle of emission of the 3 charged pions. The values thus determined for the τ are such that decay into two pions is forbidden, and on this basis the τ and θ are held to be separate entities.

[4] R. H. Dalitz, Phys. Rev. **94**, 1046 (1954); *Proceedings of the Fifth Annual Rochester Conference on High-Energy Physics* (Interscience Publishers, Inc., New York, 1955), p. 140.

[5] Kerth, Stork, Birge, Haddock, and Whitehead, Phys. Rev. **99**, 641(A) (1955); Birge, Stork, Haddock, Kerth, Peterson, Sandweiss, and Whitehead, Phys. Rev. **99**, 335 (1955).

[6] See Ritson, Pevsner, Fung, Widgoff, Zorn, Goldhaber, and Goldhaber, Proceedings of the International Conference on Elementary Particles, Pisa, 1955 (unpublished), for a preliminary report on this experiment.

[7] Goldhaber, Goldsach, and Lannuti, University of California Radiation Laboratory Report UCRL-2928, 1955 (unpublished).

done by mounting a large aluminum plate on the microscope stage and attaching it so that it could be moved in both coordinate directions. The nuclear plates were placed on this stage in such a position that the zones where the K-particle tracks ended were under observation.[8]

Following the scanning, which was conducted for stopping K-particles, the events with gray or flat minimum secondaries were chosen for analysis. Special large microscopes were used for this purpose.[9] These microscopes were so constructed as to allow aligning of particle tracks parallel to a coordinate movement, thus greatly accelerating the tracing of the near-minimum secondaries. With such microscopes, the following of tracks in our large plates was found to be easily feasible, thus obviating the necessity of cutting the plates.

SCANNING

In the scanning, all stopping particles in a defined zone were observed and those with secondaries emanating therefrom were recorded. The zone that was scanned on each plate was that in which K-particles with masses of $\sim 1000\ m_e$ and momenta of approximately 330 Mev/c were expected to end. This was determined by using the average range of the protons stopping in the plate being scanned. In this way, 766 K-events were observed, of which 693 had single near-minimum secondaries,[10] 15 had single gray secondaries (with $I/I_{\min} > \sim 2$) and 58 were identified as τ mesons by their decay into 3 charged particles. Our efficiencies ϵ for detecting these classes of K-particles in area scanning are estimated to be: $\epsilon > 75\%$ for K_L-mesons, $\epsilon > 85\%$ for K-particles with single gray secondary tracks, and $\epsilon > 90\%$ for τ mesons. These estimates were made by comparing the ratios τ/K_L and τ/τ' found in this experiment with those found by systematic "along the track" scanning.[11]

ANALYSIS

Among the 708 K-particles observed (not counting τ mesons), 51 were selected as having secondary tracks suitable for analysis. These events were chosen by using the following criteria: (1) near-minimum secondaries were selected only if they had actual dip angles $< 8°$, and if their directions were such that ranges in the stack of at least 12 cm and traversals of at least 20 emulsions were possible (34 events); (2) all dark gray secondary tracks ($I/I_{\min} > \sim 2$) were included, regardless of their angles of dip (15 events); (3) grain density measurements were made on sixty relatively flat secondary tracks, and those with $I/I_{\min} > \sim 1.4$, with dip angles $< 16°$, were chosen (2 events).

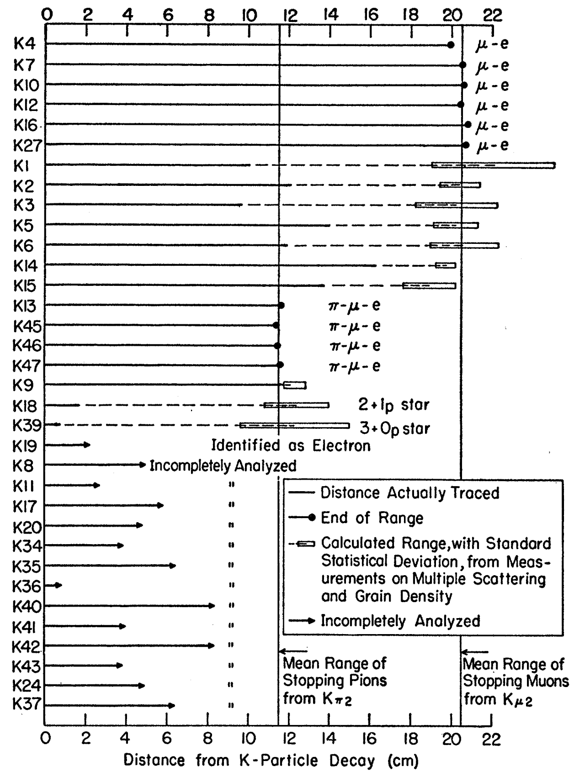

FIG. 2. Ranges of secondaries of K_L-mesons.

Whenever possible, these secondaries were traced until they came to rest in the emulsion and could be identified by their decay modes. The measurement of range was made by taking the coordinates on the microscope of the beginning and end of the track and calculating the range, assuming the track to be straight. To this range was added a correction for the deviation of the track from a straight line. This correction could be calculated easily from the detailed sets of coordinates recorded as the track was followed from plate to plate. The range thus determined was the actual distance traveled by the secondary in the stack (whose effective density was 3.85 g/cm^3).

In those cases in which the secondaries could not be followed to the ends of their ranges, multiple-scattering measurements or specific-ionization determinations or both were employed to indicate their identities. These measurements were made using standard techniques, and all such measurements, as well as the following of secondaries, were carried out on the specially constructed large microscopes.

Figures 2 and 3 show the measured or estimated

[8] In area scanning for stopping particles in plates exposed to particles of a given momentum, only a limited area of the plate needs to be covered, thus permitting the simple adaptation of a standard stage (with a 2 in.×3 in. movement) to hold "big plates." The Leitz stage (No. 48) was found particularly suitable.

[9] G. T. Zorn, Rev. Sci. Instr. (to be published).

[10] For these K-particles, which decay into single lightly-ionizing secondaries, we use the general term K_L-mesons.

[11] Birge, Haddock, Kerth, Peterson, Sandweiss, Stork, and Whitehead, Proceedings of the International Conference on Elementary Particles, Pisa, 1955 (unpublished); Chupp, Goldhaber, Goldhaber, Johnson and Webb, Proceedings of the International Conference on Elementary Particles, Pisa, 1955 (unpublished).

TABLE I. K_L-particles.

(A) Events with near-minimum secondaries followed to the ends of their ranges

Event	Range of secondary (cm) (accurate to 1 mm)	Decay of secondary	K-particle decay scheme	Mass of K-particle (m_e) From Q of decay	From range relative to mean τ range, with $m_\tau=965\ m_e$
$K4$	19.9	μ-e	$K_{\mu2}$	950 ± 14	971 ± 25
$K7$	20.5	μ-e	$K_{\mu2}$	964 ± 14	963 ± 25
$K10$	20.6	μ-e	$K_{\mu2}$	967 ± 14	971 ± 25
$K12$	20.4	μ-e	$K_{\mu2}$	962 ± 14	960 ± 25
$K16$	20.8	μ-e	$K_{\mu2}$	972 ± 14	966 ± 25
$K27$	20.7	μ-e	$K_{\mu2}$	969 ± 14	980 ± 25
$K13$	11.6	π-μ-e	$K_{\pi2}$	966 ± 8	968 ± 25
$K45$	11.35	π-μ-e	$K_{\pi2}$	959 ± 8	1013 ± 25
$K46$	11.5	π-μ-e	$K_{\pi2}$	963 ± 8	934 ± 25
$K47$	11.6	π-μ-e	$K_{\pi2}$	966 ± 8	939 ± 25

(B) Events with near-minimum secondaries that left the stack

Event	Distance followed (cm)	Ionization measurements Distance from origin (cm)	$g/g_{\min}$	Scattering measurements Distance from origin (cm)	$p\beta$ (Mev/c)	Identity of secondary (consistent with $g/g_{\min}$ and $p\beta$)	Estimated total range of secondary (cm)	K-particle decay scheme	K-particle mass (from range relative to mean τ range, with $m_\tau=965\ m_e$)
$K1$	10.1	9.2	1.13 ± 0.04	0.46	194 ± 33	μ	22 ± 3	$K_{\mu2}$	983 ± 25
$K2$	12.1	6.5	1.13 ± 0.03	8.5	150 ± 9	μ	20.4 ± 1.0	$K_{\mu2}$	954 ± 25
$K3$	9.7	6.8	1.03 ± 0.04	6.4	161 ± 13	μ	20.2 ± 2.0	$K_{\mu2}$	934 ± 25
$K5$	14.1	12.4	1.25 ± 0.05	13.0	110 ± 11	μ	20.2 ± 1.1	$K_{\mu2}$	970 ± 25
$K6$	12.0	9.8	1.08 ± 0.05	10.8	134 ± 13	μ	20.6 ± 1.7	$K_{\mu2}$	939 ± 25
$K14$	16.3	16.1	1.57 ± 0.06	...	...	μ	19.7 ± 0.5	$K_{\mu2}$	960 ± 25
$K15$	13.7	12.6	1.32 ± 0.06	...	...	μ	18.9 ± 1.3	$K_{\mu2}$	932 ± 25
$K9$[a]	11.75	...	...	8.0	94 ± 8	π	12.0 ± 0.7	$K_{\pi2}$	966 ± 25
$K18$[b]	1.7	0.7	1.19 ± 0.03	0.7	180 ± 18	π	12.4 ± 1.6	$K_{\pi2}$	923 ± 25
$K39$[c]	0.84	0.15	1.17 ± 0.10	0.56	172 ± 26	π	12.3 ± 2.7	$K_{\pi2}$	999 ± 25
$K19$	2.2	0.17	1.06 ± 0.05	0.17	76 ± 11	e	...	K_{e3}	983 ± 25

[a] From the appearance of the track as it left the stack, the estimated residual range was $\sim300\mu$.
[b] Inelastically scattered in flight, producing a $2+1p$ star.
[c] Interacted in flight, producing a $3+0p$ star.

total ranges for the light and gray tracks, respectively. It can be seen that each of the six known decay modes is represented among those identified: the numbers of identified examples, other than τ mesons, are 13 $K_{\mu2}$, 7 $K_{\pi2}$, 1 K_{e3}, 7 $K_{\mu3}$, and 10 τ' particles. Thirteen of the flat near-minimum secondaries were abandoned because they became too steep to permit unambiguous identification. Except in the special cases, $K18$, $K19$, $K39$, no K_L-secondary was identified unless the track had been followed at least 9.5 cm through the stack.

TABLE II. Events with gray secondaries.

Event	Range of secondary (cm)	Energy of secondary[a] (Mev)	Decay of secondary	K-particle decay scheme	K-particle mass (m_e) (from range relative to mean τ range, with $m_\tau=965\ m_e$)
$K22$	1.85	30.2	μ-e	$K_{\mu3}$	953 ± 25
$K23$	0.13	6.5	μ-e	$K_{\mu3}$	989 ± 25
$K25$	0.69	16.9	μ-e	$K_{\mu3}$	928 ± 25
$K30$	0.07	4.6	μ-e	$K_{\mu3}$	987 ± 25
$K38$	1.01	21.1	μ-e	$K_{\mu3}$	934 ± 25
$K44$	0.19	8.1	μ-e	$K_{\mu3}$	975 ± 25
$K52$	0.23	9.0	μ-e	$K_{\mu3}$	926 ± 25
$K26$	2.9	44.3	π-μ-e	τ'	967 ± 25
$K28$	0.34	12.6	π-μ-e	τ'	972 ± 25
$K29$	0.22	9.9	π-μ-e	τ'	970 ± 25
$K31$	1.4	28.7	π-μ-e	τ'	954 ± 25
$K32$	0.78	20.4	π-μ-e	τ'	996 ± 25
$K33$	0.86	21.5	π-μ-e	τ'	937 ± 25
$K48$	0.29	11.5	π-μ-e	τ'	968 ± 25
$K49$[b]	(1.4 ± 0.3)	(28.7)	Interacts in flight	τ'	934 ± 25
$K50$	0.30	11.8	π-μ-e	τ'	977 ± 25
$K51$	0.87	21.7	π-μ-e	τ'	991 ± 25

[a] See reference 16.
[b] At 0.2 cm, $p\beta=48\pm6$ Mev/c.

The knowledge of the identity of these 38 K-particles presented the possibility of determining the masses of the primary particles decaying in the various modes. This was done through a comparison at the same momentum of the ranges of K-mesons in each group with those of τ mesons ending in the stack. Determinations of the average K_L-particle mass have been made and were reported at the Pisa conference.[12] We have used the same procedure in this investigation to determine the mass value for the particles decaying in the various modes, relative to $m_\tau=965\ m_e$. In addition, where the secondaries were followed to the ends of their ranges, the K_L-particle masses were determined from knowledge of the decay scheme and of the Q value. The individual mass values are listed in Tables I

[12] Birge, Haddock, Kerth, Peterson, Sandweiss, Stork, and Whitehead, Proceedings of the International Conference on Elementary Particles, Pisa, 1955 (unpublished); Fung, Mohler, Pevsner and Ritson, Proceedings of the International Conference on Elementary Particles, Pisa, 1955 (unpublished).

and II and the average values for the particles decaying in each mode are given in Table III.

RESULTS AND DISCUSSION

As is noted in Figs. 2 and 3, all the known decay modes of K-particles were observed. In this section, each mode will now be considered separately, and the details regarding the characteristics of the parent particle and its decay will be discussed.

$K_{\mu 2}$

The $K_{\mu 2}$ is a meson which decays into two particles one of which is a muon of high energy. Thirteen examples of this decay mode have been observed, and of these, six secondaries were followed to the ends of their ranges. Details of these events appear in Table I. Considering the effect of straggling in range, these events are consistent with a decay into a μ meson of unique energy. The average range of the stopping muons observed is (20.48 ± 0.25) cm,[13–15] and using the range-energy curves of Barkas[16] normalized to the emulsion density of our stack, this range value corresponds to an energy of emission of (151.8 ± 1.5) Mev for the muon. The errors quoted arise from an estimated 2.7% straggling in range[17] and from the uncertainty in the stack density.

The mass of the $K_{\mu 2}$, as has been previously noted, may be determined through a comparison of its range with the τ range at any point in the stack. This is actually a comparison of the ranges of τ and K-particles at the same momentum. The individual masses obtained in this way are listed in Table I and their average value is $(960\pm7)m_e$. Using this datum and the average energy of the muon secondaries, we have calculated the mass of the neutral secondary to be ~0. The decay scheme $K_{\mu 2}^+\rightarrow\mu^+ +\nu+Q$[18,19] is therefore confirmed.

For the purpose of comparison, we may also calculate, given the decay scheme and the energies of the secondary muons, the masses of the $K_{\mu 2}$'s observed. These values are listed in Table I for the particles whose secondaries were followed to the ends of their ranges. The average value is $(964\pm6)m_e$.

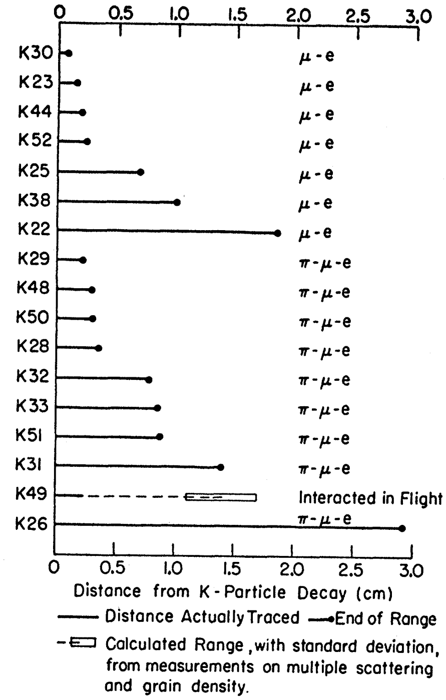

FIG. 3. Ranges of gray secondaries of K-mesons.

$K_{\pi 2}$

Of the 7 particles identified as decaying into charged pions of high energy ($E>\sim50$ Mev), 4 secondaries were followed to the ends of their ranges, one was followed almost to the end of its range, and two were identified by their nuclear interaction in flight. Details of these events appear in Table I. One observes that the pions are emitted with a unique range indicating a K-meson decay into two particles. The average pion range is (11.51 ± 0.15) cm,[15,20,21] which corresponds to

TABLE III. Average mass values for K-particles.

Decay mode	K-particle mass values (m_e) From Q of decay	From range relative to mean τ range, with $m_\tau=965\ m_e$ [a]
$K_{\mu 2}^+\rightarrow\mu^+ +\nu+Q$	964 ± 6	960 ± 7
$K_{\pi 2}^+\rightarrow\pi^+ +\pi^0+Q$	964 ± 4	963 ± 9
$K_{e3}^+\rightarrow e^+ +?+?+Q$	...	983 ± 25
$K_{\mu 3}^+\rightarrow\mu^+ +\pi^0+\nu+Q$?	...	955 ± 9
$\tau'\rightarrow\pi^+ +\pi^0+\pi^0$	...	967 ± 8

[a] The masses of the K-particles obtained from momentum-range relative to $m_\tau=965\ m_e$ agree within the errors with the results given by Birge *et al.*[12]

[13] The average muon ranges reported by Merlin *et al.*[14] for 6 cases, and Crussard *et al.*[15] for 3 cases are (20.52 ± 0.33) cm and (20.33 ± 0.33) cm, respectively, in good agreement with this value.

[14] M. Merlin *et al.*, Proceedings of the International Conference on Elementary Particles, Pisa, 1955 (unpublished).

[15] Crussard, Fouche, Kayas, Leprince-Ringuet, Morellet, Renard, and Trembley, Proceedings of the International Conference on Elementary Particles, Pisa, 1955 (unpublished).

[16] W. H. Barkas and D. M. Young, University of California Radiation Laboratory Report UCRL-2579(Rev) (unpublished); see also D. O. Caldwell, Phys. Rev. **100**, 291 (1955), for a discussion of the range-energy relation. *Note added in proof.*—The Barkas range-energy relationship has been confirmed to better than 1% by Barkas *et al.* (private communication), thus permitting greater confidence in values of the masses derived from the ranges of secondaries.

[17] K. R. Symon, Harvard University, thesis, 1948 (unpublished); B. Rossi, *High Energy Particles* (Prentice-Hall, Inc., New York, 1952), pp. 36–37.

[18] The absence of a high-energy γ ray associated with the decay, which has been indicated by a number of investigations,[19] suggests the neutrino as the neutral secondary with ~0 rest mass.

[19] Bridge, DeStaebler, Rossi, and Sreekantan, Nuovo cimento Series 10, **1**, 874 (1955); H. DeStaebler and B. V. Sreekantan, Phys. Rev. **98**, 1520 (1955); H. Courant, Phys. Rev. **99**, 282 (1955).

[20] This value of the pion range is in agreement with the value of (11.71 ± 0.33) cm given by Crussard *et al.* (1 case)[15] and the value of (11.78 ± 0.23) cm given by O'Ceallaigh *et al.* (4 cases).[21]

[21] C. O'Ceallaigh *et al.*, Proceedings of the International Conference on Elementary Particles, Pisa, 1955 (unpublished).

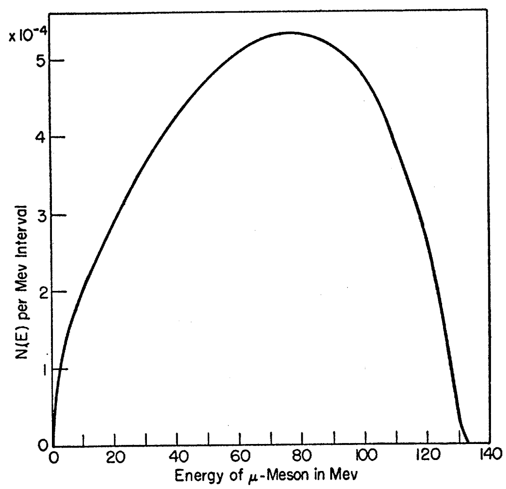

FIG. 4. Differential spectrum of μ mesons from $K_{\mu3}$ decay, under the assumption that the spectrum is proportional to the phase space factor for the three body decay $K_{\mu3}\rightarrow\mu+\pi^0+\nu$. The spectrum is normalized to total area 1/20. ($K_{\mu3}/K_L=1/20$.)

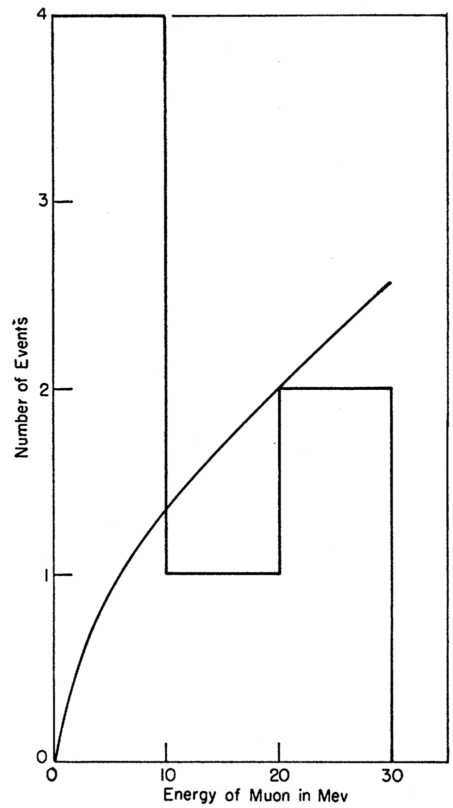

FIG. 5. Observed distribution in energy of μ mesons from $K_{\mu3}$ decay, and the calculated curve taken from the spectrum of Fig. 4, with 700 K_L events.

an average pion energy at emission of (107.8±0.9) Mev.[16] Again, the error arises from the straggling in range,[17] and from the uncertainty in the stack density.

The masses of the $K_{\pi2}$ particles have been determined through a comparison, at the same momentum, of their ranges with those of τ mesons. The values obtained in this way are listed in Table I. The average value has been calculated to be $(963\pm9)m_e$.

Using these data on the primary mass and the pion energy at emission, we may determine the mass of the neutral secondary: The value so determined is $(259\pm18)m_e$. This mass value is consistent with that of the π^0 and the decay scheme, $K_{\pi2}^+\rightarrow\pi^++\pi^0+Q$,[22] is thus confirmed.

For purposes of comparison, we have calculated the masses of those $K_{\pi2}$ particles with ending secondaries from the energy of the charged pion and the above decay scheme. These values have been listed in Table I. Their average value is $(964\pm4)m_e$.[23]

K_{e3}

In this investigation only a single example of a decay into an electron has been observed. This event may be associated with the decay of the K_{e3}. The secondary, which was identified by specific ionization loss and multiple scattering measurements, was emitted at an energy of 70 Mev. The mass of the parent particle, from a comparison of its range with the τ range was found to be $(983\pm25)m_e$. Further details on this event appear in Table I.[24]

$K_{\mu3}$

A comparatively rare event is the $K_{\mu3}$, of which 7 examples were observed. Details on each event appear in Table II. These events were identified on tracing the secondaries to the ends of their ranges by the μ-e decays there observed. The mass values, which are listed in Table II, have been calculated by comparing the range of each $K_{\mu3}$ with the τ-meson range in the stack. The average value obtained was $(955\pm9)m_e$.

Considering all available data, a reasonable decay scheme for the $K_{\mu3}$ is: $K_{\mu3}^+\rightarrow\mu^++\pi^0+\nu+Q$, and the best estimate for its frequency of occurrence relative to K_L mesons generally is $\sim1/20$. Under the assumption that the spectrum is proportional to the phase space factor for this 3-body decay, we have calculated the energy spectrum and normalized it to correspond to a $K_{\mu3}$ to K_L ratio of 1/20. This distribution is shown in Fig. 4. Our data on the distribution in energy of the

[22] A more direct indication that the neutral secondary is indeed a π^0 meson is obtained from multiplate cloud-chamber data on S-particles, where the γ rays from π^0 decay are detected.[19]

[23] We can use the data in a different fashion to determine the mass of the $K_{\pi2}$ without using the Barkas range-energy relation, the validity of which is not completely certain at high energy. From measurements of the primary mass value of the $K_{\mu2}$ relative to the τ, we have a mass value of $(960\pm7)m_e$ for the $K_{\mu2}$ (see also reference 12). If one assumes a constant ionization potential, the range of the μ secondary of (20.48±0.25) cm can then be used to provide an accurate experimental range-energy calibration, from which we obtain a value of $(961\pm6)m_e$ for the $K_{\pi2}$ mass.

[24] It should be noted that the mass value determined in this way should be viewed with some reserve, for it is uncertain, with only one event, that our zones of observation included the most probable range for the K_{e3} particle.

TABLE IV. Summary of information on $K_{\mu3}$ events: The expected numbers, calculated from the spectrum of Fig. 4, and the observed numbers in each range interval are given, for several experiments.

Source of data		I $0 \leqslant R_\mu < 1.5$ cm	II $1.5 \leqslant R_\mu < 5$ cm	III $R_\mu \geqslant 5$ cm	Proper time of flight (sec)	$K_{\mu3}/\tau'$ (low energy, $R<1.5$ cm)	Remarks
The present experiment	Expected	4.0	0.92	0.96	1.5×10^{-8}	0.7 ± 0.3	
	Observed	6	1	0			
G stack[a]	Expected	1.95	0.52	1.4	$\sim10^{-9}$	...	
	Observed	0	4	0			
Ecole polytechnique[b] (emulsion)	Expected	0.78	0.29	0.80	$\sim10^{-9}$	(1)	
	Observed	1	0	0			
Birge *et al.*[c]	Expected	2.99	0.12	..	$\sim10^{-8}$	(0.2)	
	Observed	2	1	...			
M.I.T. cloud chamber data[d]	Expected	...	...	1.2	$\sim2\times10^{-9}$	...	More conservatively, the number in Group III is: <2
	Observed	...	...	0			
Pooled cosmic-ray data[e]		...	...	...	...	1 ± 0.6	There is one well-established example of a high-energy $K_{\mu3}$ secondary: Br24, 77 Mev
Total	Expected	9.7	1.85	4.4			
	Observed	9	6	0			

[a] M. W. Friedlander *et al.*, Proceedings of the International Conference on Elementary Particles, Pisa, 1955 (unpublished).
[b] See reference 15.
[c] Birge, Haddock, Kerth, Peterson, Sandweiss, Stork, and Whitehead, Proceedings of the International Conference on Elementary Particles, Pisa, 1955 (unpublished).
[d] See reference 19.
[e] Dilworth, Occhialini, and Scarsi, Ann. Rev. Nuc. Sci. 4, 271 (1954).

muon secondaries appear in Fig. 5, where the low-energy end of the calculated spectrum is also drawn for comparison.

Our data on $K_{\mu3}$ may be conveniently divided into three groups:

The first group consists of those events in which the secondary is emitted at a sufficiently high ionization to be readily distinguishable from a minimum-ionizing secondary, irrespective of the inclination of the track. This includes muons of range <1.5 cm.

The second group consists of particles that were selected by a rough grain density measurement on flat tracks. Muons of ranges between 1.5 cm and 5.0 cm were detected in this way.

The third group consists of events in which the secondary particle had near-minimum ionization and could be identified only by following very flat tracks.

In Table IV, the observed data, divided into these groups, are compared with the expected values deduced from the spectrum of Fig. 4, which has been normalized to a $K_{\mu3}/K_L$ ratio of 1/20. These calculated values have been evaluated by taking into account the number of K-particles investigated in each ionization group. Also summarized in this table are data obtained by other groups using emulsion and cloud-chamber techniques, together with the numbers expected in each case.

Although there is fair agreement between the observed spectrum and the calculated values obtained by using the assumed spectrum and the ratio $K_{\mu3}/K_L = 1/20$, there is some indication that the number of low-energy secondaries (groups I and II) is, relatively, too high. This observation, and the fact that there have been no $K_{\mu3}$ events observed with high-energy secondaries ($R_\mu > 5$ cm), indicate that either the form of the predicted spectrum or the assumed decay scheme is incorrect.[25]

$K_{\pi3}$ or τ'

Ten examples of heavy-meson decay into a charged pion, with energy between 9.5 and 45 Mev, have been observed. These events may be interpreted as examples of the decay of the τ' or $K_{\pi3}$ particle. The masses of the primary particles have been estimated through comparison of their ranges with the τ range, and an average value of $(967\pm8)m_e$ has been obtained. The details of each event observed appear in Table II.

The energy spectrum of the secondary pions is presented in Fig. 6. The fact that such events are, indeed, examples of the alternate decay mode of the $\tau(\tau' \rightarrow \pi^+ + \pi^0 + \pi^0 + Q)$ is strongly indicated, firstly by

[25] If we choose to assume decay schemes such as $K_{\mu3}^+ \rightarrow \mu^+ + \nu + \nu + Q$ or $K_{\mu3}^+ \rightarrow \mu^+ + \nu + \gamma + Q$, an even larger discrepancy is observed between the experimental distribution and the predicted one.

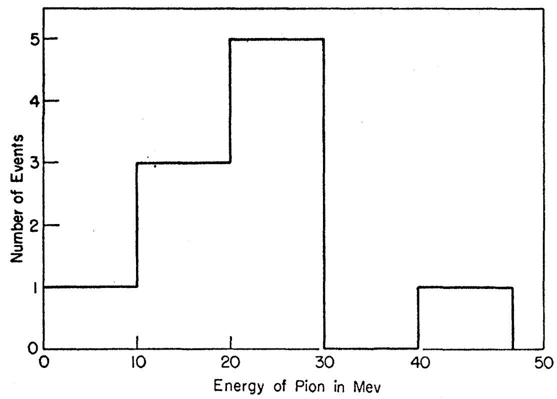

FIG. 6. Observed distribution in energy of pions from $K_{\pi 3}$ (τ') decay.

the fact that in no case, either in our data or in previously reported data, has there been observed a pion with energy greater than 53 Mev, the maximum for this scheme (except, of course, the pion from $K_{\pi 2}$ decay) and secondly, by the observed form of the pion energy spectrum (see Fig. 6 and reference 4).

RELATIVE FREQUENCIES AND LIFETIMES

The relative frequencies of the various modes of decay have been obtained from our data. For the K_L-particles, the estimates of relative frequency have been based mainly on the sample of 21 unambiguously identified events listed in Table I. However, in estimating the frequency of the K_{e3} mode, account has been taken of 24 additional K_L events (13 in this stack and 11 in another M.I.T. stack) which were incompletely analyzed, so that only the K_{e3} mode could be excluded.

A summary of the information obtained is given in Tables IV and V. For easy comparison, the results of other investigations on relative frequencies are also given there, together with the average K-particle time of flight for each experimental arrangement.

Using the experimental data obtained in this investigation and comparing them with results obtained in other ways, the mean life of the $K_{\mu 2}$, the $K_{\pi 2}$, and the $K_{\mu 3}$ may be estimated. Data currently available indicate that the lifetime for K_L-mesons (which include primarily $K_{\mu 2}$ and $K_{\pi 2}$ particles) is $\sim 1\times 10^{-8}$ sec.[26]

Since the K_L-particles have been demonstrated to be mainly $K_{\mu 2}$, the quoted lifetime is a close approximation to that of the $K_{\mu 2}$. The uncertainty lies in the lifetime estimates for the $K_{\pi 2}$. That this particle has approximately the same lifetime as the $K_{\mu 2}$ is evidenced by the comparison of our data on relative frequency with that of the G stack and the large stack of the Paris group. The close similarity of these results under experimental conditions involving very different times of flight suggests rather strongly that the lifetime of the $K_{\pi 2}$ is indeed $\sim 10^{-8}$ sec.

The lifetime of the τ meson has also recently been determined. Harris and Orear, and Alvarez and Goldhaber have independently obtained values of $\sim 1\times 10^{-8}$ sec.[27]

If we assume that the τ' has a lifetime closely similar to that of the τ, then we may hope to estimate the lifetime of the $K_{\mu 3}$. The early emulsion data (see Table IV) for $K_{\mu 3}$ and τ' decaying into low energy muons and pions (ranges <1.5 cm) indicate a ratio of $K_{\mu 3}/\tau'$ ~ 1. This is in good agreement with our ratio of 0.7, thus indicating that the $K_{\mu 3}$ also has a mean life of $\sim 10^{-8}$ sec.

One might expect that any difference among K-particles decaying in various ways would exhibit itself in production. That is to say, the excitation curves for production and the energy spectra might be different for particles decaying in the several modes. Evidence to the contrary, although not of a very conclusive sort, is implied by the fact that the relative frequencies of occurrence of the various decay modes observed under the widely different conditions of cosmic-ray experiments and Bevatron exposures are in agreement.

Data on the decay of the τ meson into three charged pions[4] strongly indicate values of spin and parity for the τ which forbid decay into two π mesons, and accordingly, suggest that the beam we observe is composed of at least two kinds of particles, thetons and tauons. The fact that the masses are identical or closely similar (Table III) could perhaps arise from some fundamental feature of the basic theory—that the lifetimes, however, are similar for the decay into two or three π mesons is either highly fortuitous or could result in a natural way from one of the two mechanisms described below.

The first explanation, advanced by Lee and Orear,[28] suggests that thetons are short-lived (lifetime $\sim 10^{-10}$ sec) and hence the beam after $\sim 1.5\times 10^{-8}$ sec is composed of longer-lived tauons. These, when they come to rest in the emulsion, can decay, among other modes, into thetons ($\tau\rightarrow\theta+\gamma$, lifetime $\sim 10^{-8}$ sec), which subsequently decay by the fast process, $\theta\rightarrow\pi+\pi^0$. This sequence of processes would result in an identical apparent lifetime of $\sim 10^{-8}$ sec for the θ and τ, and also, the relative frequencies of the two decay modes would be the same under all conditions of observation. However, if a short-lived K-particle exists, it is surprising that it has not been observed in nuclear emulsions or cloud chambers.

[26] Chupp, Goldhaber, Goldhaber, Iloff, Lannutti, Pevsner, and Ritson, International Conference on Elementary Particles, Pisa, 1955 (unpublished); L. Mezetti and J. W. Keuffel, Phys. Rev. **95**, 858 (1954); Barker, Binnie, Hyams, Rout, and Shepherd, Phil. Mag. **46**, 307 (1955); K. W. Robinson, Phys. Rev. **99**, 1606 (1955); L. Alvarez *et al.*, Phys. Rev. **101**, 503 (1956); give $\sim 1.3\times 10^{-8}$ sec for both $K_{\mu 2}$ and $K_{\pi 2}$; V. Fitch and R. Motley, Phys. Rev. **101**, 496 (1956), gives $(12.1_{-1.0}^{+1.1})\times 10^{-9}$ sec for the $K_{\pi 2}$, $(11.7_{-0.7}^{+0.8})\times 10^{-9}$ sec for the $K_{\mu 2}$.

[27] Harris, Orear, and Taylor, Nevis Cyclotron report R-111, August 1955 (unpublished); L. Alvarez and S. Goldhaber, Nuovo cimento, Series 10, **2**, 344 (1955).

[28] T. D. Lee and J. Orear, Nevis Cyclotron report R-112, August, 1955 (unpublished).

TABLE V. Relative frequencies of occurrence of the various modes of decay. (For $K_{\mu3}$, see Table IV.)

Source of data	Proper time of flight (sec)		K_L-mesons $K_{\mu2}$	$K_{\pi2}$	K_{e3}	τ/K_L	τ/τ'
The present experiment	1.5×10^{-8}	Numbers observed	13/21	7/21	1/45	1/12	4.6/1[a]
		Percentages	63%	34%	2%		
G-stack[b]	$\sim10^{-9}$	Numbers observed	21	17	5	...	...
		Percentages	49%	39%	12%		
Ecole Polytechnique[c] (emulsion)	$\sim10^{-9}$	Numbers observed	16	9	2	1/18	...
		Percentages	59%	33%	7%		
M.I.T. cloud chamber data[d]	$\sim2\times10^{-9}$	Numbers observed	24	9	...	...	...
		Percentages	~70%	~30%	...		
Birge *et al.*[e]	$\sim10^{-8}$	Numbers observed	...	...	...	1/11	4.1/1
		Percentages	...	...	...		

[a] This ratio has been corrected to take account of relative scanning efficiency for τ and τ' particles.
[b] A. Bonetti *et al.*, Proceedings of the International Conference on Elementary Particles, Pisa, 1955 (unpublished).
[c] See reference 15.
[d] See reference 19.
[e] See reference c of Table IV.

The second proposal makes use of the fact that any charged particle of mass $\sim1000\ m_e$ which decays via the universal Fermi interaction[29] into a $\mu+\nu$ should have a lifetime of $\sim5\times10^{-9}$ sec. Charged thetons and tauons should both be able to decay by this mode, giving rise to the experimentally observed $K_{\mu2}$ particles. If this decay process is the fastest for both, then the lifetimes of the charged theton and tauon will of course be largely determined by the $\mu+\nu$ decay mode, and will be closely similar, though not identical.[30,31]

CONCLUSION

In this investigation, we have observed K^+ particles which came to rest in a large emulsion stack $\sim1.5\times10^{-8}$ sec after their production in the Bevatron.

Through analysis of their charged secondaries, the decay schemes for $K_{\mu2}$, $K_{\pi2}$, and τ' particles have been confirmed, and a decay scheme for the $K_{\mu3}$ has been discussed.

From our results it has been possible to estimate the relative frequencies of occurrence of the various modes of decay (Tables IV and V). These results, taken together with data on relative frequencies as detected under different experimental conditions and with measurements of K_L- and τ-meson lifetimes, indicate that, within the experimental accuracy, all the decay modes are associated with lifetimes of $\sim1\times10^{-8}$ sec. Also, comparison of the relative frequencies of occurrence of the various modes as measured in this experiment and in other investigations indicates no striking energy dependence of production of K-particles decaying in different ways.

Comparison of the masses of particles decaying in the various modes (Table III), shows that if a mass difference exists, it is smaller than $\sim10\ m_e$.

Thus, no evidence was obtained in this investigation of any gross difference in mass, lifetime or production among K-particles. The discussion in the preceding section indicates that this is not necessarily inconsistent with the existence of two separate particles.

ACKNOWLEDGMENTS

We would like to take this opportunity to thank Dr. E. Lofgren and the staff of the Bevatron for making this exposure possible and to gratefully acknowledge the help of Dr. L. Kerth and W. Chupp, who set up the meson channel for the exposure. We are grateful to J. Lannutti for help in preparing the stack for exposure, and to the Richman group for x-ray marking the stack.

We would also like to express our appreciation to Dr. L. S. Osborne for stimulating discussions and for his help in planning this experiment, and to Professor B. T. Feld for many helpful discussions.

Finally, we would like to thank Dr. N. Mohler, Dr. E. Manaresi, and Miss D. Fournet for their aid in the analysis, and Mrs. T. Kallmes, Mrs. A. Lane, Miss C. Warren, Mrs. G. Lanza, and Mrs. N. Pal for their excellent work in the scanning of plates.

[29] Enrico Fermi, *Elementary Particles* (Yale University Press, New Haven, 1951).

[30] The neutral thetons and tauons will not be able to decay through a $\mu+\nu$ mode, there being no neutral μ meson. Thus, if the above explanation for the similar lifetimes of charged thetons and tauons is correct we should expect very different lifetimes for the two neutral counterparts.

[31] The suggestion that the lifetimes of the charged theton and tauon could be similar because of the dominance of the $K_{\mu2}$ mode of decay was made independently to one of us by A. Pais.

Note added in proof.—The slight indications in Table V of possible differences in proportions of the K_{e3} component persist in more extensive data of J. R. Peterson [Phys. Rev. **100**, 1803 (A) (1955)] and of the École Polytechnique.