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Experimental Survey of Strange Particle Decays

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I. INTRODUCTION

It is the aim of these three lectures to summarize the present experimental knowledge concerning the decays of the strange particles. Lifetimes and branching ratios of the heavy mesons are tabulated in Table I and those of the hyperons in Table II.

It is well known, that although the universal "V-A" theory gives a good description of what we presently know of the weak interactions of non-strange particles, no such simple model exists for the decays of strange particles. The situation is more complex for several reasons, one of them being the existence of decays which do not involve leptons and neutrinos, the so-called non-leptonic decays. Nevertheless, substantial regularities are emerging; among those the following can be listed:

1) $|\Delta S| \leq 1$. This rule forbids decays such as $\Xi \to N + \pi$, which are not observed. It is also linked in certain theoretical models with the mass differences of the K_1^o and K_2^o .

2) $\Delta S = \Delta Q$. This rule states that the change in strangeness of the strongly interacting particles in decays which involve a strangeness change should be equal to the change in electric charge. The rule, for instance,

forbids the decay $\Sigma^+ \to n + L^+ + \nu$, whereas the decay $\Sigma^- \to n + L^- + \bar{\nu}$ is allowed.

3) The lepton current in leptonic decays has the same form as in the universal theory of β and μ decay: $J_{L_\mu} = \bar{u}_L \gamma_\mu (1 + \gamma_5) u_\nu$. This rule has the consequences that the strong current in these decays must transform as a vector or pseudovector, and must be the same for muon and electron decays.

4) $\Delta I = 1/2$. This rule states that the change in the isotopic spin of the strongly interacting particles in a decay is one-half. Alternatively, it can be stated as follows: Isotopic spin in a decay involving strangeness change is conserved, if it is postulated that a particle of zero mass, spin and momentum, and isotopic spin 1/2 is absorbed by the decaying particle. Examples of the prediction of the $\Delta I = 1/2$ rule are:

(a) $$\frac{\Gamma(\Lambda^o \to \pi^- + p)}{\Gamma(\Lambda^o \to \pi^o + n)} = 2$$ (non-leptonic),

(b) $\Sigma^+ \to e^+ + n + \nu$ is forbidden (leptonic) .

It is noted that theoretical models which incorporate the $\Delta I = 1/2$ rule for leptonic decays, do not necessarily have this property for non-leptonic decays, and vice versa. It seems, therefore, important to check this question experimentally separately for the two types of decay.

5) A "universal" model based on SU_3 and certain other assumptions has been proposed by Cabibbo.[18] It relates the strangeness changing leptonic decays to the neutron and pion decays, and seems to be in substantial agreement with the altogether too sparse data.

In the following we present the experimental data against this theoretical background.

II. K-MESON DECAYS

A. General Discussion

The K's form two spin zero doublets:

$$K^+ , K^o ; S = +1; \qquad \bar{K}^o , K^- ; S = -1$$

It follows from the CPT theorem that the K^+ and K^- decay rates are equal, and we will not treat these decays separately. The K^o and $\bar{K}^o$ require some discussion. These neutral particles cannot be expected to decay independently, but must be expected to be mixed by the decay Hamiltonian, as first pointed out by Gell-Mann and Pais.[35] There will be two states, $K_1{}^o$ and $K_2{}^o$, mixtures of K^o and $\bar{K}^o$, which diagonalize the Hamiltonian. There is good reason to believe that the weak interaction conserves C.P.*, and in this case the proper mixtures are easy to

* If C.P. is conserved, then the $K_2{}^o$ decay to two pions is forbidden. It has just been shown very convincingly by J.H. Christensen, J.W.Cronin, V.L.Fitch, and R.Turlay, Phys. Rev. Letters 13, 138 (1964) that the longlived $K_1{}^o$ has a small, but nonzero, branching ratio to two pions

$$\frac{\Gamma_{2(\pi^+\pi^-)}}{\Gamma_{2(\text{all decays})}} \simeq 0.002 .$$ This corresponds to a C.P. violation in K^o decay of the order of 2 parts in one thousand in amplitude. The violation of C.P. is of fundamental

find, since they must conserve C.P. They are:

$$K_1^o = \frac{1}{\sqrt{2}} (K^o + \bar{K}^o) \qquad CP = +1$$

$$K_2^o = \frac{1}{\sqrt{2}} (K^o + \bar{K}^o) \qquad CP = -1$$

These decay exponentially, so that the time dependence of K_1^o K_2^o amplitudes can be written:

$$K_1^o(t) = K_1^o(o)\, e^{-\Gamma_1 t/2}$$

$$K_2^o(t) = K_2^o(o)\, e^{-\Gamma_2 t/2}$$

The time dependence of amplitudes initially K^o or $\bar{K}^o$ is then:

$$K^o(t) = \frac{1}{\sqrt{2}} \left[K_1^o(o)\, e^{-\Gamma_1 t/2} + K_2^o(o)\, e^{-\Gamma_2 t/2} \right]$$

$$\bar{K}^o(t) = \frac{1}{\sqrt{2}} \left[K_1^o(o)\, e^{-\Gamma_1 t/2} - K_2^o(o)\, e^{-\Gamma_2 t/2} \right]$$

The decay rates of K_1^o and K_2^o into the various channels are in general unequal. The lifetime of the K_1^o is $(0.87 \pm 0.02) \times 10^{-10}$ sec, that of the K_2^o is 5.4×10^{-8} sec.[40] The decay into two pions, which is dominant by a factor of ~ 500 in K_1^o decay, is forbidden by C.P. invariance to the K_2^o, and this is the reason for the long lifetime of the K_2^o. The experimental test for C.P. invariance is more sensitive than

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importance in the understanding of the weak interaction, but the observed violation is not large enough to invalidate the arguments presented in the following for experiments of presently obtainable accuracy.

this. It is known that the branching ratio of the K_2^o to two pions is less than 1/2 % (A. Michellini[47], Luers et al[45]), so that $\Gamma_2(\pi^+\pi^-) / \Gamma_1(\pi^+\pi^-) < 10^{-5}$. (See, however, note on page 3).

B. $K \rightarrow 2\pi$

We have experimentally

$$\Gamma_1(\pi^+\pi^-) + \Gamma_1(\pi^o\pi^o) = (1.11 \pm 0.05) \times 10^{10} sec^{-1}$$

$$\Gamma_1(\pi^+\pi^-) / \Gamma_1(\pi^o\pi^o) = 2.33 \pm 0.07 \qquad a$$

$$\Gamma_+(\pi^+\pi^-) = 1.5 \times 10^7 sec^{-1} \qquad b$$

The K^+ decay rate to two pions is lower by a factor of approximately 700 than the K^o two pion decay. This experimental fact prompted the postulate of the $\Delta I = 1/2$ rule (Pais[50]). The $\Delta I = 1/2$ predictions are, remembering that the two pions must be in an S state because the K spin is zero and that the isotopic spin of the two pions must therefore be even, and because of the $\Delta I = 1/2$ rule, equal to zero:

$$\Gamma_1(\pi^+\pi^-) / \Gamma_1(\pi^o\pi^o) = 2.00$$

$$\Gamma_+(\pi^+\pi^o) = 0$$

The large suppression of the K^+ decay can then be understood in terms of the approximate validity of the $\Delta I = 1/2$ rule,

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a Experimental results on this ratio have been summarized by Chretien et al[22].

b Alexander et al[3], Birge et al[13], Roe et al[51].

and the non-zero rate as a violation of the rule to the extent of an admixture of $\Delta I = 3/2$ and $5/2$ of the order of 5% in amplitude. This amount of admixture can also yield the small deviation of the experimental $\Gamma_1(\pi^+\pi^-) / \Gamma_1(\pi^o\pi^o)$ ratio from the expected ratio. The magnitude of the violation seems to be too large to be understandable as an electromagnetic effect.

C. $K^+ \rightarrow \mu^+ + \nu$ and $K^+ \rightarrow e^+ + \nu$

1. Relative Rates and the Form of the Lepton Current

The $K^+ \rightarrow \mu^+ + \nu$ decay accounts for 65% of charged K decay. The electron decay has not yet been found, but is at any rate weak: $\Gamma_+(e^+\nu) / \Gamma_+(\mu^+\nu) <$).005 . The weakness of the electron decay finds its parallel in π-decay. The pion-electron decay is found to be 10,000 times weaker than the pion-muon decay, and the relative rates are accurately given by a lepton current of the form $\bar{u}_L \nu_\mu (1 + \nu_5) u_\nu$, which brings with it a factor m_L/m_π in the amplitude. Presumably this is also the explanation in the case of the kaon. The argument provides the most sensitive test presently available in strange particel decay for the absence of scalar, pseudoscalar and tensor lepton currents.

2. Polarization of the Muon

The helicity of the muon in K^+ decay must be the same as that in pion decay, if leptons are conserved. This is in agreement with the experiment of Coombes et al[24].

D. $K \to 3\pi$

We concern ourselves with the four reactions:*

	Reaction	Relative Phase Space
a)	$K^+ \to \pi^+\pi^-\pi^+$	1.000
b)	$K^+ \to \pi^+\pi^o\pi^o$	1.244
c)	$K_2^o \to \pi^+\pi^-\pi^o$	1.284
d)	$K_2^o \to \pi^o\pi^o\pi^o$	1.566

For each reaction a distribution in two independent variables (two outgoing energies, two angles connecting outgoing tracks, etc.) can be tabulated. Study of reaction (a) and the analysis of Dalitz[28] led to the conclusion that the K^+ has zero spin and odd parity, and together with the $K^+ \to 2\pi$ decay which,with zero spin,must have even parity, led to the question of the conservation of parity. At present,interest centers on the validity of the $\Delta I = 1/2$ rule in relating processes (a) - (d).

The final state has many isotopic possibilities and the analysis is by no means trivial. Note, for example, that three different state of isotopic spin 1 are possible. The

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* The decay rate of the K_1^o into three pions is expected to be small if CP invariance is valid, since the decay is forbidden into pions of zero relative angular momentum and the barriers for the higher angular momentum states are expected to be large. This decay has not been found experimentally.

main arguments are due to Dalitz[29], Sawyer and Wali[53], and Weinberg[60]. The relationships for the total rates, based on $\Delta I = 1/2$ (and in certain cases additional assumptions about the final state interactions) are:

e) $\gamma_2(+-0) = 2\gamma_+(+00)$

f) $\gamma_2(000) = \gamma_+(++-) - \gamma_{+(+00)}$

g) $\gamma_+(++-) = 4\gamma_+(+00)$

We have written a lower case γ for the square of the matrix element, or the rates divided by phase space, since phase space varies appreciably from reaction to reaction.

In addition, as Weinberg[60] has shown, linear relationships of the form

$$w(T)\,dT = \left(1 + \beta \frac{3T\ Q}{m_k} \right) \phi\ (T)\,dt \qquad (1)$$

for the energy spectra can be expected. Here T is the kinetic energy of one of the pions, Q is the total kinetic energy available to the pion system and $\phi(T)$ is phase space. The following relationships for the β coefficients can be expected if $\Delta I = 1/2$:

h) $\beta_2^o(+-0) = \beta_+^+(+00)$

i) $\beta_+^+(+00) = -2\beta_+^-(++-)$

j) $\beta_2^o(000) = 0$

The superscript is the charge of the pion.

In Table III, the observed rates, as well as the rates divided by the relative phase space factor are given. The results for relations (e), (f), (g) are given in Table IV. Relations (f) and (g) are in good agreement with the experiment, and relationship (e) is in error by two standard deviations.

The experimental data on the energy spectrum are the following: all experiments at present can be adequately analyzed in terms of the linear relation (1). As examples, we show in Fig. 1 the results of Ferro-Luzzi et al[33], and in Fig. 2 those of Kalmus et al[41]. The coefficients are given in Table V.

It can be seen that both relations (h) and (i) are consistent with the data. No data exist for relation (j), but this relations follows in any case from the identity of the pions.

E. Leptonic Decays, the $K_1 - K_2$ Mass Difference and $\Delta S = \Delta Q$

1. Formulation

If $\Delta S = \Delta Q$, the transitions

$$\left.\begin{array}{ll} a) & K^o \rightarrow \pi^- + L^+ + \nu \\ b) & \bar{K}^o \rightarrow \pi^+ + L^- + \nu \end{array}\right\} \qquad \text{amplitude} \equiv 1$$

are allowed while the transitions

c) $K^0 \rightarrow \pi^+ + L^- + \nu$

d) $\bar{K}^0 \rightarrow \pi^- + L^+ + \nu$ amplitude = x

are forbidden. We assume CP invariance, so that x is real. If $\Delta S = \Delta Q$, $x = 0$. The time distribution of $L^\pm$ decays, given a beam initially composed only of K^0 , will then be:

$$[L^\pm(t)] = \frac{N^0\Gamma_{2L}}{4} \left| \frac{(1+X)}{(1-X)} e^{-\Gamma_1 t/2} \pm e^{-\Gamma_2 t/2 + i\Delta m t} \right|^2$$

$$= \frac{N^0\Gamma_{2L}}{4} \left\{ \frac{(1+X)^2}{(1-X)^2} e^{-\Gamma_1 t} + e^{-\Gamma_2 t} \pm 2\frac{(1+X)}{(1-X)} \cos(\Delta m t) e^{-(\Gamma_1+\Gamma_2) t/} \right. \quad (2)$$

where Γ_{2L} is the transition probability for K_2 lepton decay, N^0 is the total $\bar{K}^0$ flux and Δm is the mass difference between K_1 and K_2. If the beam is initially $\bar{K}^0$, the sign of the Δm term reverses. If the beam is initially an incoherent equal mixture of the two, the interference term containing Δm drops out.

2. Mass Difference

The strong and electromagnetic interactions, because they conserve strangeness, cannot produce a differene in the $K_1{}^0$ and $K_2{}^0$ masses. However, the weak interaction has non-vanishing matrix elements connecting the K^0 and $\bar{K}^0$, and this results in the mixing which has already been dixcussed. It also results in a removal of the mass degeneracy. The transition $K^o \rightleftharpoons \bar{K}^o$ is of the type $|\Delta S| = 2$. If such transitions are allowed, the mass difference is expected to be of order of magnitude $\Delta m \simeq G m_k^3 \simeq 10^{19}$ sec^{-1}. This is a very large mass difference and is not observed. Such terms would also produce the transition $\Xi \to N + \pi$. If such terms are absent the process is expected to be of second order in G, and the mass difference may be expected to be of the order of $\Delta m \simeq G^2 m_k^5 \simeq 10^{11}$ sec^{-1}. This is comparable to the K_1^o decay rate Γ_1. It is customary to express Δm in units of Γ_1.

The mass difference has been observed in experiments on the "regeneration" of K_1^o mesons in the traversal of dense material by a beam of K_2^o. The most recent result of this type (Christensen et al[23]) is in agreement with the earlier results of Good et al[37], $|\Delta m|/\Gamma_1 = 0.84 \pm 0.25$. Camerini et al[21] study the time dependence of $\bar{K}^o$ type interactions (hyperon production) of neutral K's produced in charge exchange collisions of a K^+ beam, and therefore, initially K^o. The K^o's are produced, and the interactions observed in the heavy liquid bubble chamber. The time dependence is expected to be of the form (2) with x = 0 and the minus sign. On the basis of 122 interactions it is found that $|\Delta m|/\Gamma_1 = 1.9 \pm 0.3$. Aubert et al[5] use the time distribution of leptonic decays described by form (3), and make the assumption (confirmed by experiment as will be detailed) that $\Delta S = \Delta Q$ and, therefore, that x = 0. The K^o mesons are produced, again in the heavy liquid bubble chamber, in K^+-nucleus collisions. On the basis of 102 observed electron and positron decays, it is concluded that $|\Delta m|/\Gamma_1 = 0.78 \pm 0.2$. There seems to be a convergence of the results to a value of $\Delta m/\Gamma_1$ between 0.5 and 1. In any case, all experiments agree on the important point that the mass difference is of the order of the K_1^o decay rate, and that there is no evidence for $|\Delta S| > 1$ currents.

3. $\Delta S = \Delta Q$

If the K beam is an incoherent mixture of K^o and $\bar{K}^o$, as is the usual experimental situation, and the time distribution of leptonic decays of either lepton charge is measured, we see from (2) that the interference term cancels and we find:

$$[L^+(t)] + [L^-(t) = \frac{N^o\Gamma_{2L}}{2}\left[\left(\frac{1+X}{1-X}\right)^2 e^{-\Gamma_1 t} + e^{-\Gamma_2 t}\right] \qquad (3)$$

The expected time distribution is the sum of two exponentials with K_1^o and K_2^o lifetime. The initial decay rate is larger by the factor $\left(\frac{1+X}{1-X}\right)^2 +1$ than that for intermediate times $\tau_1 << t << \tau_2$. If $\Delta S = \Delta Q$, $\alpha = \left(\frac{1+X}{1-X}\right)^2 = 1$. The distribution (4) has been studied by Ely et al[32] in the heavy liqued chamber. K^o's are produced in K^+ + nucleus collisions and decays producing electrons or positrons observed by inspection on the basis of the characteristic behavior of slow electrons in the heavy liquid chamber. A large excess in the initial decay rate is observed on the basis of 28 events, corresponding to $\alpha = 12 \pm 6$. The probability that the experimental result is compatible with $\Delta S = \Delta Q$ is given as less than 1%. This has spurred other attempts to confirm the result. The Columbia-Rutgers group (Kirsch et al[42]) produces neutral K mesons in the annihilation of antiprotons in the liqued hydrogen bubble chamber. All V's are measured and leptonic decays selected kinematically. This technique requires much more measurement, since the leptonic decays account for only 1% of the observed K decays, but it has some substantial advantages. On the basis of 45 leptonic decays it is concluded that the time distribution is closely that expected on the basis of $\Delta S = \Delta Q$ (see Fig. 3). A best fit to (3) yields $\alpha = 0.85\ ^{+1.7}_{-0.85}$, in disagreement with the earlier result. An experiment using essentially the same technique as Ely et al[32], but more extensive and differing somewhat in the selection criteria for the events (Aubert et al[5]) gives a result also in agreement with $\Delta S = \Delta Q$ on the basis of 102 leptonic decays. A best fit yields $\alpha = 1.3\ ^{+1.2}_{-0.7}$.

4. Dynamics of K-meson Leptonic Decay

(a) General Form. Assuming that the lepton current is local, the matrix element is of the form

$$m = G \sum F_j \ \bar{u}_L(p_L) \ O_j\left(\frac{1+\gamma_5}{\sqrt{2}}\right) \ u_\nu(p_\nu)$$

with the interaction $F_j O_j$ of the form

Scalar $\quad m_k f_s(q^2)$

Vector $\quad i\left[f_1(q^2)\ (P_k+P_\pi)_\alpha + f_2(q^2)\ (P_k-P_\pi)_\alpha\right]\gamma_\alpha$

Tensor $\quad \left[f_T(q^2)/m_k\right](P_{k\alpha}P_{\pi\beta})\ (\gamma_\alpha\gamma_\beta - \gamma_\beta\gamma_\alpha)$

q is the momentum transfer to the leptons. $q = P_k - P_\pi$.

In the vector case, there are two independent terms. It should be noted that the term in f_2 can, with a simple transformation, be put into the form $Gf_2(q^2)\ m_L\ \bar{u}_L \frac{(1+\gamma_5)}{\sqrt{2}}\ u_\nu$. It has become usual to write $\xi(q^2) = f_2/f_1$. Then the vector matrix element becomes:

$$M_v = i\ Gm_k\ f_1\ (q^2)\ \bar{u}_L\left[\frac{(P_k+P_\pi)_\alpha}{m_k}\ \gamma_\alpha - i\ \xi(q^2)\frac{m_L}{m_k}\right]\frac{(1+\gamma_5)}{\sqrt{2}}\ u_\nu \qquad (4)$$

In the case of the electron the ξ^2 term is negligible because of the smallness of the electron mass. In the case of the muon, the experimental problem becomes that of determining $f_1^{\,2}(q^2)$ and $\xi^2(q^2)$.

(b) $K \rightarrow e + \nu + \pi$. The experimental data indicate that the interaction form is vector, with a form factor which is nearly constant. In the experiment of Luers et al[45], 153 $K_2^{\,o} \rightarrow e^\pm + \pi^\pm + \nu$ events in the H_2 bubble chamber were analyzed and found to be incompatible with a pure tensor interaction, compatible with a scalar interaction only if the form factor is assumed to vary by a factor greater than ten over the small range in momentum transfer of the decay, but compatible with vector with constant f_1 . Brown et al[17], and Jensen[39] analyze K^+ decays in the Xenon bubble chamber. The information in each event consists chiefly of the emission angles of the two photons from π^o decay and the electron. It is found, on the basis of $\sim$ 400 K_{e3}^+ decays, permitting the form factor to vary to give the best possible fit, that the data can fit a pure vector interaction with 50% probability, but that the best tensor and scalar fits have probabilities of less than 0.1%. The comparison of data for the π^o opening angle in the case of constant form factor is given in Fig. 4.

(c) $K \rightarrow \mu + \nu + \pi$. The experimental data are consistent with universal coupling for electron and muon with pure vector interaction and ξ (q^2) small, possibly zero.

Assuming vector interaction and universality, as well as negligible form factor variation in the small q^2 interval of this decay, (4) can be integrated to yield the ratio R of $K_{\mu 3}$ and K_{e3} total rates as a function of ξ:

$$R(\xi) = 0.65 + 0.124\ \xi + 0.0190\ \xi^2 \quad . \quad \text{(Bisi et al[15])}.$$

Shaklee et al[54] find $R = \frac{0.03 \pm 0.01}{0.046 \pm 0.003} = 0.65 \pm 0.2$, while Bisi et al[15] find R = 0.7 ± 0.14 . These values are compatible with either $\xi \cong 0$ or $\xi \cong -6.5$. The spectrum in $K_{2\mu 3}^o$ has been studied by Abashian et al[1]. On the basis of 2000 events obtained in a spark chamber arrangement, it is concluded that the interaction is vector, with $\xi = +1 \pm 1$ (another value of ξ, $\xi = -4 \pm 1$ is compatible with the data but incompatible with R). The comparison of the data with theoretical expectation is shown in Fig. 5.

The $K^+_{\mu 3}$ decay has been studied extensively by Bisi et al[15], combining the use of the hydrogen chamber for the low momentum region with the heavy liquid chamber for the high momentum region. On the basis of $\sim$ 1000 events, it is concluded that the data are consistent with the vector interaction with a small value of ξ (see Fig. 6). The best fit is with $\xi = -2$ but $\xi = 0$ cannot be excluded.

The polarization of the muon in $K^+_{\mu 3}$ decay has been studied by two groups and is also sensitive to ξ . Already the work of Smirnitsky and Weissenberg[55] indicated a small value of ξ . The recent work of Gidal et al[36] gives an average polarization of the muon of $\langle P_\mu \rangle = +0.74 \pm 0.16$ for the muon energy interval $38 < T_\mu < 96$ MeV . This corresponds to $\xi = -0.15 \pm 0.9$ (or -4.0 ± 0.8).

(d) K_{L3} Decay and the $\Delta I = 1/2$ Rule. If the $\Delta I = 1/2$ rule applies to the leptonic decays, then

$$\Gamma_{1L} = \Gamma_{2L} = 2\Gamma_{+L} \qquad (5) ,$$

and of course, the form of the interaction must be the same for all decays. We have already seen in Sec. II, E-3, that the experimental evidence favors $\Gamma_{1L} = \Gamma_{2L}$. In the preceding paragraphs we have seen that vector coupling with $\xi \cong 0$ is in agreement with the evidence for both K^+ and K_2^o decay. It remains to compare the absolute rates. Until recently the data on the total decay rates were in disagreement with (5). (Alexander et al [2]). The discrepancy has however been removed with the appearance of new experimental results, especially also in the $K^+_{\mu 3}$ branching ratio. The results on the K^+ branching ratios are:

$\Gamma_{+\mu 3}/\Gamma_+$	$= 0.030 \pm 0.01$	Xenon Chamber	Shaklee et al [54]
	$= 0.035 \pm 0.003$	H_2 and Heavy Liquid Chamber	Bisi et al [15]
Γ_{+e3}/Γ_+	$= 0.046 \pm 0.003$	Xenon Chamber	Shaklee et al [54]

These, combined with the K^+ lifetime, yield:

$$\Gamma_{+\mu 3} = (2.78 \pm 0.25) \times 10^6 \text{ sec}^{-1}$$

$$\Gamma_{+e3} = (3.75 \pm 0.25) \times 10^6 \text{ sec}^{-1}$$

$$\Gamma_{+L3} = \Gamma_{+\mu 3} + \Gamma_{+e3} = (6.53 \pm 0.35) \times 10^6 \text{ sec}^{-1}$$

For the K_2^o leptonic decays, the results are the following:
(a) A recent direct determination of the total leptonic decay in the hydrogen chamber yields $\Gamma_{+L} = (11.9 \pm 1.5) \times 10^6 \text{ sec}^{-1}$ (Kirsch et al [43]). (b) Luers et al[45] find for the ratio of leptonic K_2 decays to all charged K_2 decays to be

$$\Gamma_{2e3}/\Gamma_{2(\text{charged})} = 0.487 \pm 0.05$$

$$\Gamma_{2\mu 3}/\Gamma_{2(\text{charged})} = 0.356 \pm 0.07 \quad .$$

The neutral K_2^o decays are probably almost entirely three π^o decays. For these Anikina et al[4] find the branching ratio

$$\Gamma_{2(\pi^o\pi^o\pi^o)} / \Gamma_{2(\text{all charged})} = 0.38 \pm 0.07 .$$

These measurements combined with the K_2^o lifetime of $(5.4 \pm 0.5) \times 10^{-8}$ sec [40] give the following decay rates

$$\Gamma_{2e3} = 6.5 \pm 1.0 \times 10^6 \text{ sec}^{-1}$$

$$\Gamma_{2\mu 3} = 4.8 \pm 1.0 \times 10^6 \text{ sec}^{-1}$$

$$\Gamma_{2L} = 11.3 \pm 1.3 \times 10^6 \text{ sec}^{-1}$$

All results agree with the $\Delta I = 1/2$ rule predictions.

(e) K_{e4} Decays. The K decays into leptons and two pions afford a convenient test of the $\Delta S=\Delta Q$ rule. The decay

i) $K^+ \rightarrow \pi^+ + \pi^- + e^+ + \nu$ is allowed, while the decay

ii) $K^+ \rightarrow \pi^+ + \pi^+ + e^- + \bar{\nu}$ is forbidden. The muon decays have not been seen. They are expected to be rare becuase the phase space is small. Two experiments have been performed[14,11,12] both in the heavy liquid bubble chamber. To date approximatiley 75 decays of type (i) have been observed, and no examples of the forbidden decay (ii) have been found in agreement with $\Delta S = \Delta Q$. This corresponds to an upper limit for the ratio of the amplitude of the $\Delta S = -\Delta Q$ transition $x < 0.2$ with 95% confidence. The branching ratio for K_{e4} decay relative to all K^+ decay,

$R_{e4} = (4.3 \pm 0.9) \times 10^{-5}$. (Birge et al[12])

III. HYPERON DECAYS

A. Non-Leptonic Decays and the $\Delta I=1/2$ Rule

1. General

There are seven known hyperons: Λ^{o}; Σ^{+}, Σ^{o}, Σ^{-}; Ξ^{o}, Ξ^{-}; and Ω^{-}. The Σ^{o} decays electromagnetically to the Λ^{o}; the decay is not through the weak interaction and will not be considered here. The others all have decays of the form hyperon → pion + baryon , and these decays dominate by factors of the order of 10^{3} the leptonic modes which are considered later. The baryons, to the extent to which it is known, all have spin one-half (the Ξ spin is not yet certain, although likely to be one-half, the Ω^{-} spin is unknown) so that the final state is a mixture of $s_{\frac{1}{2}}$ and $p_{\frac{1}{2}}$. The decay is described by the distributions in the final momentum and polarization vectors $\vec{q}$ and $\vec{P}_B$ in terms of the initial polarization $\vec{P}_Y$. This can be done with the help of the three parameters α, β and γ, of which two are independent.

$$I(\hat{q}) = 1 + \alpha\vec{P}_Y \cdot \hat{q}$$

$$\vec{P}_B = [(\alpha+\vec{P}_Y \cdot\hat{q})\hat{q}+\beta\vec{P}_Y \times \vec{q} +\gamma\hat{q} \times(\vec{P}_Y \times \hat{q})]/(1+\alpha\vec{P}_Y \cdot\hat{q})$$

The parameters α, β and γ are related to the relative amplitudes and phases of the s and p waves:

$$\alpha = \frac{2\mathrm{Re}\ S\ p^*}{(S)^2+(p)^2}\ ; \quad \beta = \frac{2\mathrm{Im}\ S\ p^*}{(S)^2+(p)^2}\ ; \quad \gamma = \frac{(S)^2-(p)^2}{(S)^2+(p)^2}$$

so that $\alpha^2 + \beta^2 + \gamma^2 = 1$.

If time reversal invariance holds, the difference between the S and p wave phases can be shown to be equal to the difference in the corresponding pion-baryon scattering phase shift.

The experimental problem reduces to the determination of the decay rates, and the correlation coefficients α, β and γ. The latter can be obtained by studying the angular distribution and polarization of the baryon for a polarized sample of hyperons. $\alpha\vec{P}_Y$ is obtained from the anisotropy of the decay momentum vector with respect to the production plane normal. α itself can be obtained by measuring the helicity of the emitted baryon. β can be determined by studying the component of the baryon polarization in the direction normal to both the production plane and the decay momentum. γ is a measure of the relative amount of S and p wave; $\gamma = +1$ for pure S wave and $\gamma = -1$ for pure p wave.

2. Λ^o Decay

a. Branching ratio. The experimental data were recently compiled by Chretien et al[22] who find

$$\frac{R_{\Lambda \to \pi^- + p}}{R_{\Lambda \to \pi^o + n}} = \frac{66.5 \pm 0.6}{33.5 \pm 0.6} = 1.98 \pm 0.06 \quad .$$

The $\Delta I = 1/2$ rule prediction is $2 \times \frac{\Phi_{\pi^- p}}{\Phi_{\pi^o n}} = 1.9$.

b. Correlations. The most accurate and extensive measurements are due to Cronin and Overseth[27] who measured angular correlations for polarized Λ's produced in $\pi^- p$ collisions. The polarization of the decay protons was analyzed by measuring the right-left asymmetry of their scatterings in the carbon plates of a spark chamber. It is found that

$$\alpha = +0.62 \pm 0.07$$

$$\beta = +0.18 \pm 0.24$$

$$\gamma = 0.78 \pm 0.06$$

$$|P|/|S| = 0.36 \begin{smallmatrix} +0.05 \\ -0.06 \end{smallmatrix}$$

The measured value of β can be compared to the value $\beta = 0.08$, which is expected on the basis of the known pion nucleon phase shifts and the measured value of α.

The parameters for the decay $\Lambda \to \pi^0 + n$ are expected to be the same if the $\Delta I = 1/2$ rule is valid. Measurements exist for $\alpha\bar{P}$ of a set of Λ's produced in $\pi^+ d$ collisions. Cork et al[25] find

$$\bar{P}\alpha = +0.55 \pm 0.06 \qquad \text{for } \Lambda^0 \to \pi^- + p$$

and $$\bar{P}\alpha = +0.60 \pm 0.13 \qquad \text{for } \Lambda^0 \to \pi^0 + n \quad .$$

3. <u>Σ Decay and the $\Delta I=1/2$ Rule</u>

There are three decays:

$$\Sigma^+ \to \pi^+ + n \quad ; \quad M^+$$

$$\Sigma^+ \to \pi^0 + p \quad ; \quad M^0$$

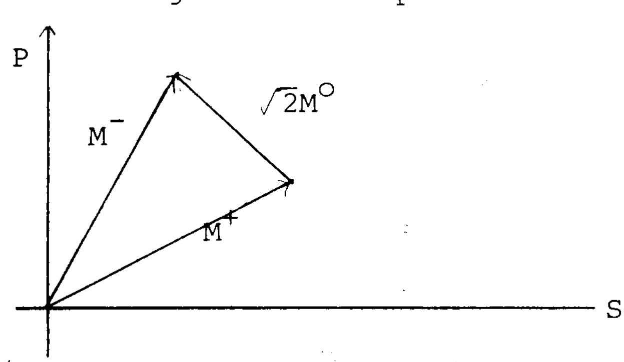
$$\Sigma^- \to \pi^- + n \quad ; \quad M^-$$

The matrix elements M^+, M^o and M^- for these decays are related by the $\Delta I=1/2$ rule. The relations are easily derived if it is assumed that the Σ's combine with a "spurion" and that isotopic spin is conserved in the transition to the pion and proton.

The "spurion" is defined as a particle of zero energy and momentum and spin, has isotopic spin one-half, and in these reactions, $I_z = 1/2$. The matrix elements can then be written in terms of the isotopic spin of the final state:

$$M^- = M_{3/2}$$
$$M^+ = (1/3)M_{3/2} + (2/3)M_{1/2}$$
$$M^o = (2/3)M_{3/2} - (2/3)M_{1/2}$$

From these the triangular relation $M^- - M^+ = \sqrt{2}\, M^o$ follows. The relative phases of $M_{1/2}$ and $M_{3/2}$ is small, since the pion nucleon phase shifts are small at this energy. If the relative phase is assumed zero, the triangular relation can be visualized in a plot in which one axis represents the S-wave amplitude and a perpendicular axis represents the p-wave amplitude. M^-, M^+ and $\sqrt{2}\, M^o$ form a triangle on this plot.



Without the $\Delta I=1/2$ rule there are six independent quantities: $\Gamma^+, \Gamma^-, \Gamma^o$ and $\alpha^+, \alpha^-, \alpha^o$ (the β's follow then from the pion nucleon phase shifts, and the absolute values of γ follows from the relations $\alpha^2 + \beta^2 + \gamma^2 = 1$).

With the $\Delta I=1/2$ rule there are four independent parameters, $S_{1/2}$, $P_{1/2}$, $S_{3/2}$ and $P_{3/2}$, so that the Γ's and α's are over-determined by two. The question of the validity of $\Delta I=1/2$ in these processes was recently raised by Tripp et al[59] and reexamined by Franzini and Zanello.[34]

The experimental data are:

τ_{Σ^+} =	0.82	$^{+0.1}_{-0.08}$	(a)
	0.765	±0.04	(b)
τ_{Σ^-} =	1.75	$^{+0.39}_{-0.30}$	(a)
	1.58	±0.06	(b)
$\frac{R_{\Sigma^+\to n+\pi^+}}{R_{\Sigma^+\to p+\pi^0}}$ =	1.00	±0.06	(a)
	0.96	±0.05	(b)
α^+ =	+0.20	±0.24	(d)
	+0.03	±0.08	(c)
α^0 =	+0.90	±0.25	(d)
	+0.73	$^{+0.16}_{-0.11}$	(e)
α^- =	+0.16	±0.21	(d)

(a) Barkas et al[8]

(b) Humphrey and Ross[38]

(c) Cork et al[25]

(d) Tripp et al[59]

(e) Beall et al[9]

This can be fitted within the $\Delta I = 1/2$ frame with

$$S_{1/2} = (-0.75 \pm 0.025) \times 10^{-13}$$
$$P_{1/2} = (\ 0.25 \pm 0.03\ ) \times 10^{-13}$$
$$S_{3/2} = (\ 0.03 \pm 0.03\ ) \times 10^{-13}$$
$$P_{3/2} = (-0.47 \pm 0.01\ ) \times 10^{13}$$

or alternatively, a set in which the roles of S and P waves are exchanged. The fit has a χ^2 of 3.3 where one would normally expect $\chi^2 \sim 2$ corresponding to the two constraints. The fit, although poorer than normal is only a weak indication that perhaps the $\Delta I=1/2$ rule is inadequate at the present level of experimental precision. The amplitudes $M_{1/2}$ and $M_{3/2}$ correspond to a Σ^- decay which is within experimental error pure P wave and $\Sigma^+ \rightarrow \pi^+$ decay which is pure S wave or vice versa.

4. $\Sigma^+ \rightarrow p + \gamma$

This decay has recently been investigated by Nauenberg[49a]. The branching ratio relative to all Σ^+ decays is

$$\frac{R(\Sigma^+ \rightarrow p + \gamma)}{R(\Sigma^+ \rightarrow \text{anything})} = 0.13 \pm 0.04 \quad .$$

5. Ξ Decays: $\Xi^- \rightarrow \pi^- + \Lambda^o$ and $\Xi^o \rightarrow \pi^o + \Lambda^o$

There has been a large improvement in the experimental knowledge of Ξ decay in the last year or two; however, little of this is published. The data were summarized by Ticho at the BNL Weak Interaction Conference of 1963.[58] The following groups contributed:

(a) CERN: H.Schneider, Physics Letters 4, 360 (1963)

(b) LRL: Alvarez, Berge, Hulbard, Kalbfleisch, Shafer, Solmits, Stevenson, Wojcicki

(c) EP: Junean, Morellet, Nguyen Kae, Petian, Rousset, Bingham, Cundy, Koch, Ronue, Sletten, Stannard, Scarr, Sparrow, Wilson, Halsteinslid, Möllernd

(d) UCLA: Carmony, Pjerron, Schlein, Slater, Stork, Ticho

(e) BNL: Bertanza, Brisson, Cermolly, Harl, Mittra, Moneti, Rau, Samios, Skillicorn, Yamamoto, Goldberg, Gray, Leitner, Lichtman, Wertgard, Phys. Rev. Letters 9, 229 (1962).

The published references refer to earlier publications of the same group, but typically the data made available to the summary were more extensive. Results from a total of 2167 Ξ^- decays and 207 Ξ^o decays were compiled.

a. Mean lives. The Ξ^- meanlife is obtained without problem. The results of all groups agree and give a best value $\tau_{\Xi^-} = 1.76 \pm 0.05 \times 10^{-10}$ sec .

The Ξ^o meanlife is troublesome because the decay point (a neutral particle decaying to neutral particles) is in general poorly established. The results of the three groups reporting on the lifetime differ somewhat:

Group	$\tau \times 10^{-10}$ sec	No. of Events
LRL	$2.42^{+0.31}_{-0.24}$	91
UCLA	$3.5^{+0.9}_{-0.7}$	54
EP	$3.8^{+1.0}_{-0.65}$	24

Combining and weighting according to the number of events, $\tau_{\Xi^o} = 2.96 \pm 0.5$. The ratio $\tau_{\Xi^o}/\tau_{\Xi^-}$ is expected to be two if the $\Delta I=1/2$ rule is valid. Experimentally, $\tau_{\Xi^o}/\tau_{\Xi^-} = 1.68 \pm 0.3$, so that the agreement of $\Delta I=1/2$ with experiment is as good as can be expected.

b. Correlation Coefficients. The decay of the Ξ lends itself particularly well to this study, because the polarization of the Λ^o can be directly observed from the distribution in the Λ decay pion. Using α=0.62±0.07 and combining the available data, Ticho finds $\alpha_{\Xi^-}=-0.48\pm0.05$, $\beta_{\Xi^-}=+0.20\pm0.17$, $\gamma_{\Xi^-}=+0.85\pm0.04$.

In the $\Delta I=1/2$ rule, the coefficients in Ξ^o decay are expected to be the same. Experimentally, only the value of α exists. Combining the results of three groups reported by Ticho according to the number of events reported, $\alpha_\Lambda\alpha_{\Xi^o}= -0.15\pm0.14$, so that $\alpha_{\Xi^o}= -0.24\pm0.23$. Again there is no evidence for violation of the $\Delta I = 1/2$ rule.

B. Leptonic Hyperon Decays

1. Decay Rates

The following table gives results presently available for the hyperon leptonic branching ratios:

Decay	Method	Branching Ratio	Reference
$\Lambda^o \to e^-+p+\nu$	HLBC	$(0.82\pm0.13)\times10^{-3}$	Ely et al[31]
	HLBC	$(0.78\pm0.12)\times10^{-3}$	Baglin et al[6]
	HBC	$(1.55\pm0.34)\times10^{-3}$	Lind et al[44]
$\Lambda \to \mu^-+p+\nu$	HBC	$(0.14\pm0.06)\times10^{-3}$	Lind et al[44]
$\Sigma^- \to e^-+n+\nu$	HBC	$(1.37\pm0.34)\times10^{-3}$	Nauenberg et al[49]
	HBC	$(1.4\pm0.3)\times10^{-3}$	Courant et al[26]
	HLBC	$(1.0^{+0.4}_{-0.3})\times10^{-3}$	C.T.Murphy[48]
$\Sigma^- \to \mu^-+n+\nu$	HBC	$(0.66\pm0.15)\times10^{-3}$	Courant et al[26]
$(\Gamma_{\Sigma^+}\to\text{lept})/(\Gamma^-\to\text{lept})$	HBC	<0.15 80% cons	Nauenberg et al[49]
		<0.12 80% cons	Courant et al[26]
		<0.4	C.T.Murphy[48]
$\Sigma^- \to \Lambda^o+e^-+\nu$	HBC	$(0.74\pm0.2)\times10^{-4}$	CERN[61] and Columbia[23a]
$\Sigma^+ \to \Lambda^o+e^++\nu$	HBC	$(0.4\pm0.2)\times10^{-4}$	CERN[61] and Columbia[23a]
$\Xi^- \to \Lambda+e^-+\nu$		$(3\pm1.7)10^{-3}$	Ticho[58]
$\Xi^o \to \Sigma^\pm+e^\mp+\nu$		$<10^{-3}$	Ticho[58]

The combined results are the following:

Decay	Branching Ratio	Decay Prob. (sec^{-1})	Relative Phase Space
$\Lambda \to e^- + p + \nu$	$(0.83 \pm 0.05) \times 10^{-3}$	3.3×10^6	1.60
$\Lambda \to \mu^- + p + \nu$	$(0.14 \pm 0.06) \times 10^{-3}$	0.56×10^6	0.174
$\Sigma^- \to e^- + n + \nu$	$(1.32 \pm 0.2) \times 10^{-3}$	8.2×10^6	9.22
$\Sigma^- \to \mu^- + n + \nu$	$(0.66 \pm 0.15) \times 10^{-3}$	4.1×10^6	3.14
$\Sigma^+ \to$ lept	$<0.1 \times 10^{-3}$	10^6	11.0
$\Sigma^- \to \Lambda^0 + e^- + \nu$	$(0.74 \pm 0.2) \times 10^{-4}$	0.46×10^6	0.0416
$\Sigma^+ \to \Lambda^0 + e^+ + \nu$	$(0.4 \pm 0.2) \times 10^{-4}$	0.5×10^6	0.0250
$\Xi^- \to \Lambda^0 + e^- + \nu$	$(3 \pm 1.7) \times 10^{-3}$	17×10^6	3.18
$\Xi^0 \to \Sigma^\pm + e^\mp + \nu$	$<10^{-3}$	$<3 \times 10^6$	0.277

The phase space figures are appended for comparison. The ratios of muon to electron decay seem to be, at least within the limited accuracy of these experiments, given by phase space; on the other hand the matrix element squared for Λ decay is larger than that for strangeness changing Σ^- decay by about a factor of two. Σ^+ leptonic decay is inhibited, presumably on the basis of the $\Delta S = \Delta Q$ rule which will be discussed below. The strangeness conserving decay $\Sigma \to \Lambda + e^- + \nu$ is relatively more rapid than the strangeness violating decays by a factor of about ten.

2. <u>$\Delta S = \Delta Q$ Rule</u>

The decays $\Sigma^+ \to e^+(\mu^+) + n + \nu$ are forbidden by this rule, while the corresponding Σ^- decays are allowed. The observed Σ^+ rate is lower by at least a factor of ten, in agreement with the rule. A possible violation of the rule, larger than the extremely small violations ($\sim G^4$) expected in the second order of the weak interaction, is however of considerable theoretical interest. There are two events reported in the literature which violate this rule; one by Barbaro-Galitieri et al[7] is a possible example of the decay $\Sigma^+ \to \mu^+ + n + \nu$ and one by Nauenberg et al[49] is a possible example of the decay $\Sigma^+ \to e^+ + n + \nu$.

The event of Nauenberg et al has a probability of 1% of being interpretable as background, while that of Barbaro-Galitieri was originally quoted as having a probability of 10^{-5} of being interpretable in terms of other processes. Since that time, however, the number of Σ^+ decays which have been investigated for this decay has increased by a factor of 10^3, so that in any case this probability must also be increased to the order of 1% . At this time the bulk of the evidence, also in the decay $K \rightarrow 2\pi + L + \nu$ and the K^0 decay is in favor of $\Delta S = \Delta Q$. A reasonable upper limit, combining all experimental results, for the $\Delta S = \Delta Q$ currents would seem to be of the order of 10%.

3. Decay Spectra and Form of the Interaction

a. $\Lambda^0 \rightarrow p + e^- + \nu$. The 100 events of Baglin et al[6] have been compared with the expectations of the theory assuming constant form factors for the possible interaction invariants which might be dominant. The Λ's here are unpolarized and two distributions were prepared: the distribution in the transverse proton momentum (the longitudinal component has an experimental ambiguity), and the distribution in the e-ν angle. The latter is not free from ambiguity since in general for each measured event there are two possible neutrino directions, and both are used. The observed distributions are in substantial disagreement with pure scalar or vector, but can be fitted with pure axial vector, pure tensor or a mixture of V and A.

The experiment of Lind et al[44], using polarized Λ, is sensitive to the V-A interference, and despite the fact that there are few (22) events, can yield both the sign and approximate ratio of the admixture, assuming the other interactions are not present. This experiment, as quoted by Bingham[10], yields the result: A - (0.9 ± 0.4) V .

A recent experiment by Rubbia et al[52] uses spark chamber techniques to study the correlation of the decay electron momentum and Λ^o polarization for a sample of Λ's produced in π^- Be collisions. The polarization of these Λ's is measured to be 0.68 ± 0.1 . On the basis of 102 events which show no correlation, the decay interaction is either pure V, or V-(0.8±0.3)A, assuming that the interaction is a VA mixture.

b. $\Sigma^{\mp} \rightarrow \Lambda + e^{\mp} + \nu$. In the experiments of the CERN[61] and Columbia[23a] groups of K^- mesons stopped in the hydrogen chamber, 22 examples of this strangeness conserving decay have been found. The data on the rates are summarized in Table VI. The experimental accuracy is so poor at this stage, that the remark may be premature, but it should be kept in mind that if $\Delta I = 1$ for the strongly interacting particle current, the two matrix elements are expected to be the same, and phase space then favors the Σ^- decay over the Σ^+ decay by the factor 1.67.

The $\Sigma^{\pm} \rightarrow \Lambda$ decay is interesting from a theoretical point of view and has been discussed by Cabibbo and Gatto[20], Dreitlein and Primakoff[30], and Cabibbo and Franzini[19]. Assuming again a leptonic current of the $\gamma_\mu(1+\gamma_5)$ form, the baryon current has the form

$$<\Lambda|J_\mu{}^\gamma|\Sigma^-> = \bar{u}_\Lambda[a(q^2)\gamma_\mu+b(q^2)\sigma_{\mu\nu}q_\nu+b'(q^2)q_\mu]u_{\Sigma^-}$$

$$<\Lambda|J_\mu{}^\Lambda|\Sigma^-> = \bar{u}_\Lambda\ [c(q^2)\gamma_\mu+d(q^2)\sigma_{\mu\nu}q_\nu+d'(q^2)q_\mu]\gamma_5 u_{\Sigma^-}$$

The terms in q_ν, (b, b', d, d') are expected to be ignorable since the momentum q_ν is less than 70 MeV. The a term is expected to be zero in the conserved vector current theory. We, therefore, expect a distribution dominated by the axial vector c term. The distributions in the Λ^o momentum are very different for the a and c terms. The experiment favors c over a and therefore A over V (see Fig. 7) by a factor of about 30, in agreement with the expectations based on CVC.

c. $\Xi^- \to \Lambda^o + e^- + \nu$

$\Xi^o \to \Sigma^\pm + e^\mp + \nu$. Three examples of Ξ^- leptonic decay are reported by Bingham[10] in a compilation of all results to yield a branching ratio of $2.4 \pm 1.4 \times 10^{-3}$, and a decay probability of $\Gamma_{\Xi^-} \to \Lambda^o + e^- + \nu = (1.4 \pm 0.8) \times 10^6\ \mathrm{sec}^{-1}$. The data relevant to Ξ^o β decay have been compiled by Ticho.[58] The effective sample of Ξ^o decays in which such decays would have been seen is 325 for the decay $\Xi^o \to \Sigma^+ + e^- + \nu$ and 400 for the decay $\Xi^o \to \Sigma^- + e^+ + \nu$. No decays of either type have been seen.

4. Comparison of the Cabibbo Model for Leptonic Decays with the Experimental Results

Cabibbo[18] has put forward a model in which the currents of the strongly interacting particles transform under SU_3 as the members of an octet. With the additional assumptions that the currents are linear combinations of vector and axial vector, and that the sum of the squares of the vector parts of the $\Delta S = 0$ and $\Delta S = \Delta Q$ currents is equal to the square of the vector part of μ decay current, several relations between various decay processes can be written. In this model, the properties (rates and correlations) of the hyperon leptonic decays, as well as the axial vector to vector ratio of neutron decay and the ratio of $K_{\mu 2}$ decay to $\pi_{\mu 2}$ decay can be given in terms of three arbitrary real parameters, in addition to an overall coupling constant.

The relations are well satisfied by the presently available data, in fact in more than one way. A least squares analysis to the data has just been performed by Willis et al[61]. The best fit is obtained with the Cabibbo parameters[18] $\theta = 0.264$, $F = 0.437$, $D = 0.742$, giving a probability for the fit of 45%. The solution also predicts the A-V ratio for the hyperon decays. In $\Lambda \to e^-$ decay the predicted ratio is -0.7, in agreement with the observed value of -0.8 ± 0.3 .[52] In $\Sigma^- \to e^-$ decay, for which there are at present no experimental results, this solution predicts the ratio $A/V \cong +0.3$.

IV. SUMMING UP

While no general, well-established theoretical model for the decays of strange particles exists, the following points can be made:

(1) The $\Delta I = 1/2$ rule has been checked in the case of the decays:

$$\Lambda \rightarrow \pi + N$$

$$\Sigma \rightarrow \pi + N$$

$$K \rightarrow \pi + \pi$$

$$K \rightarrow \pi + \pi + \pi$$

$$K \rightarrow L + \nu + \pi$$

and is in good agreement both in the case of leptonic and non-leptonic decay, with the exception of a violation in amplitude of approximately 5% in the $K \rightarrow 2\pi$ decay.

(2) The $\Delta S = \Delta Q$ rule is at least approximately valid. It is checked in the decays:

$$K_2 \rightarrow L + \pi + \nu$$

$$\Sigma \rightarrow L + \pi + \nu$$

$$K \rightarrow 2\pi + e + \nu$$

and the violating amplitudes are at most of the order of 20%.

(3) The strangeness change is at most 1. $|\Delta S| \leq 1$.

(4) The lepton current for all leptonic decays is compatible with the form:

$$\bar{u}_L \gamma_\mu (1 + \gamma_5) u_\nu + c.c.$$

(5) The Cabibbo scheme based on SU_3 shows promise of being able to relate the various leptonic decay processes of strongly interacting particles.

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Table 1

K decays, lifetimes, branching ratios.

Decay	τ	Branching Ratios	Γ sec^{-1}
$K^+ \to \mu^+ + \nu$	1.224×10^{-8}	0.65 ± 0.02	5.32×10^7
$K^+ \to \pi^+ + \pi^0$		0.19 ± 0.01	1.5×10^7
$K^+ \to \pi^+ + \pi^- + \pi^+$		0.059 ± 0.003	0.485×10^7
$K^+ \to \pi^+ + \pi^0 + \pi^0$		0.017 ± 0.002	0.14×10^7
$K^+ \to \pi^0 + e^+ + \nu$		0.046 ± 0.003	0.376×10^7
$K^+ \to \pi^0 + \mu^+ + \nu$		0.030 ± 0.010	0.245×10^7
$K^+ \to \pi^+ + \pi^- + e^+ + \nu$		$(4.3 \pm 0.9) \times 10^{-5}$	3.5×10^3
$K^+ \to \pi^+ + \pi^+ + e^- + \nu$		$< 10^{-6}$	$< 10^2$
$K_1^0 \to \pi^+ + \pi^-$	$(0.87 \pm 0.02) \times 10^{-10}$	0.70 ± 0.02	0.80×10^{10}
$K_1^0 \to \pi^0 + \pi^0$		0.30 ± 0.02	0.34×10^{10}
$K_2^0 \to \pi^+ + \pi^- + \pi^0$	$(5.4 \pm 0.5) \times 10^{-8}$	0.125 ± 0.013	2.3×10^6
$K_2^0 \to \pi^0 + \pi^0 + \pi^0$		0.27 ± 0.05	5.1×10^6
$K_2^0 \to e + \nu + \pi$		0.36 ± 0.04	6.7×10^6
$K_2^0 \to \mu + \nu + \pi$		0.26 ± 0.06	4.9×10^6
$K_2^0 \to$ lept.		0.62 ± 0.05	11.6×10^6

Table 2

	τ	Branching ratios	Decay Probability Γ
$\Lambda\to\pi^-+p$	$(2.5\pm0.1)\times10^{10}$ sec	0.665 ± 0.006	$2.66\times10^{9}\,sec^{-1}$
$\to\pi^o+\eta$		0.335 ± 0.006	$1.34\times10^{9}\,sec^{-1}$
$\to e^-+\nu+p$		$(0.83\pm0.05)\times10^{-3}$	$3.3\times10^{6}\,sec^{-1}$
$\to\mu^-+\nu+p$		$(0.14\pm0.06)\times10^{-3}$	$0.56\times10^{6}\,sec^{-1}$
$\Sigma^-\to\pi^-+\eta$	$(1.6\pm0.06)\times10^{-10}$ sec	1.00	$0.625\times10^{10}\,sec^{-1}$
$\to e^-+\nu+\eta$		$(1.3\pm0.2)\times10^{-3}$	$0.82\times10^{7}\,sec^{-1}$
$\to\mu^-+\nu+\eta$		$(0.66\pm0.15)\times10^{-3}$	$0.41\times10^{7}\,sec^{-1}$
$\to\Lambda^o+e^-+\nu$		$(0.74\pm0.2)\times10^{-4}$	$0.046\times10^{7}\,sec^{-1}$
$\Sigma^+\to\pi^++\eta$	0.78×10^{-10} sec	0.49 ± 0.025	$0.63\times10^{10}\,sec^{-1}$
$\to\pi^o+p$		0.51 ± 0.025	$0.65\times10^{10}\,sec^{-1}$
$\to e^++\nu+\eta$		$<10^{-4}$	$<0.05\times10^{+7}\,sec^{-1}$
$\to\mu^++\nu+\eta$		$<10^{-4}$	$<0.05\times10^{7}\,sec^{-1}$
$\to\Lambda^o+e^++\nu$		$(0.4\pm0.2)\times10^{-4}$	$0.05\times10^{7}\,sec^{-1}$
$\to p+\gamma$		$(1.3\pm0.4)\times10^{-3}$	$1.7\times10^{7}\,sec^{-1}$
$\Xi^o\to\Lambda^o+\pi^o$	$(2.96\pm0.5)\times10^{-10}$ sec	1.0	$0.34\times10^{10}\,sec^{-1}$
$\Xi^-\to\Lambda^o+\pi^-$	$(1.76\pm0.05)\times10^{-10}$ sec	1.0	$0.57\times10^{10}\,sec^{-1}$
$\Omega^-\to\Xi^o+\pi^-$			
$\Omega^-\to\Xi^-+\pi^o$			1 event seen
$\Omega^-\to\Lambda^o+K^-$			1 event seen

Table III

Summary of results on $K \to 3\pi$ decay rates

Reaction	$\Gamma^{+}(x10^{6}sec^{-1})$		$\gamma(x10^{6}sec^{-1})$
$K_{+}(++-)$	4.85 ± 0.16	(a)	4.85 ± 0.16
$K_{+}(+00)$	1.45 ± 0.11	(a)	1.16 ± 0.09
$K_2^o(+-0)$	2.34 ± 0.32	(b)	
	2.3 ± 0.4	(c)	
	2.32 ± 0.25	(d)	1.80 ± 0.20
$K_{2}(000)$	5.1 ± 1.0	(e)	3.26 ± 0.6

(a) This is the combined result of Barkas et al,[8] Taylor et al[57] and Roe et al[51].

(b) Combined results of Stern et al[56] and Kirsch et al[43].

(c) Results of Luers et al[45] using also the K_2^o lifetime of Jovanovitch et al[40] and the $\Gamma_{2(000)}/\Gamma_{2(charged)}$ branching ratio of Anikina et al[4].

(d) The combined result b and c

(e) Branching ratio of Anikina et al[4] and lifetime of Jovanovitch et al[40].

Table IV

Comparison of experimental 3 pion decay rates with the $\Delta I = 1/2$ rule expectations.

Relation	$\Delta I = 1/2$ Rule Expectations	Experiment
i)	$\gamma_{2(+-0)} / \gamma_{+(+00)} = 2$	1.55 ± 0.21
ii)	$\gamma_{2(000)} / [\gamma_{+(++-)} - \gamma_{+(+00)}] = 1$	0.91 ± 0.18
iii)	$\gamma_{+(++-)} / \gamma_{+(+00)} = 4$	4.2 ± 0.33

Table V

Experimental Determinations of the Linear Coefficients in the Energy Spectra of one of the Pions in $K \to 3\pi$ Decay. (See text for definition of β. The superscript on β stands for the charge of the pion.)

Coefficient	Value		Combined Value
$\beta^{-}_{+(++-)}$	1.67 ± 0.26	(a)	
	1.69 ± 0.27	(b)	
			1.68 ± 0.20
$\beta^{+}_{+(+00)}$	-3.95 ± 1.2	(c)	
	-4.13 ± 0.35	(d)	
			-4.1 ± 0.35
$\beta^{o}_{2(+-0)}$	-4.1 ± 0.9	(e)	
	-4.2 ± 0.6	(f)	
			-4.2 ± 0.5

(a) McKenna et al[46]

(b) Ferro-Luzzi et al[33]

(c) Bjorklund et al[16]

(d) Kalmus et al[41]

(e) Luers et al[45]

(f) Abashian et al[1]

Table VI

Summary of data on the rates for the decays $\Sigma^{\pm} \rightarrow \Lambda^{o} + e^{\pm} + \nu$.

	$\Sigma^{-}\rightarrow\Lambda+e^{-}+\nu$	Σ^{-} in sample	$\frac{R(\Sigma^{-}\rightarrow\Lambda+e^{-}+\nu)}{R(\Sigma^{-}\rightarrow\text{anything})}$	$\Sigma^{+}\rightarrow\Lambda+e^{+}+\nu$	Σ^{+}in sample	$\frac{R(\Sigma^{+}\rightarrow\Lambda+e^{+}+\nu)}{R(\Sigma^{+}\rightarrow\text{anything})}$
CERN	11	147,000	$(0.75\pm0.3)\text{x}10^{-4}$	4	60,000	$(0.66\pm0.35)\text{x}10^{-}$
Columbia	6	83,000	$(0.72\pm0.3)\text{x}10^{-4}$	0	38,600	0
Total	17	230,000	$(0.74\pm0.2)\text{x}10^{-4}$	4	98,600	$(0.4\ \pm0.2)\text{x}10^{-}$

FIGURE CAPTIONS

Fig. 1 Enegry Spectrum, after Division by Phase Space, of the Odd Pion in $K^{\pm}\rightarrow\pi^{\pm}+\pi^{\mp}+\pi^{\mp}$. (Ferro-Luzze et al[33]).

Fig. 2 Energy Spectrum of the π^{+} in the Decay $K^{+}\rightarrow\pi^{+}+2\pi^{0}$ (Kalmus et al[42]).

Fig. 3 Time Distribution of Leptonic K^{0} Decays in Experiment of Kirsch et al[42]. Solid Curve is Expectation if $\Delta S = \Delta Q$.

Fig. 4 $K^{+} \rightarrow e^{+} + \nu + \pi^{0}$ distribution in γ-γ opening angle. (Jensen[39])

Fig. 5 Muon Energy Spectrum in $K^{0}_{2\mu 3}$ Decay divided by the expectation of Formula 5. (Abashian et al[1]).

Fig. 6 Muon Kinetic Energy Spectrum in $K^{+}_{\mu 3}$ Decay. (Bisi et al[15]).

Fig. 7 Λ^{0} momentum distribution in the decay $\Sigma^{-} \rightarrow \Lambda^{0} + e^{-} + \nu$ (CERN[61] and Columbia[23a]).

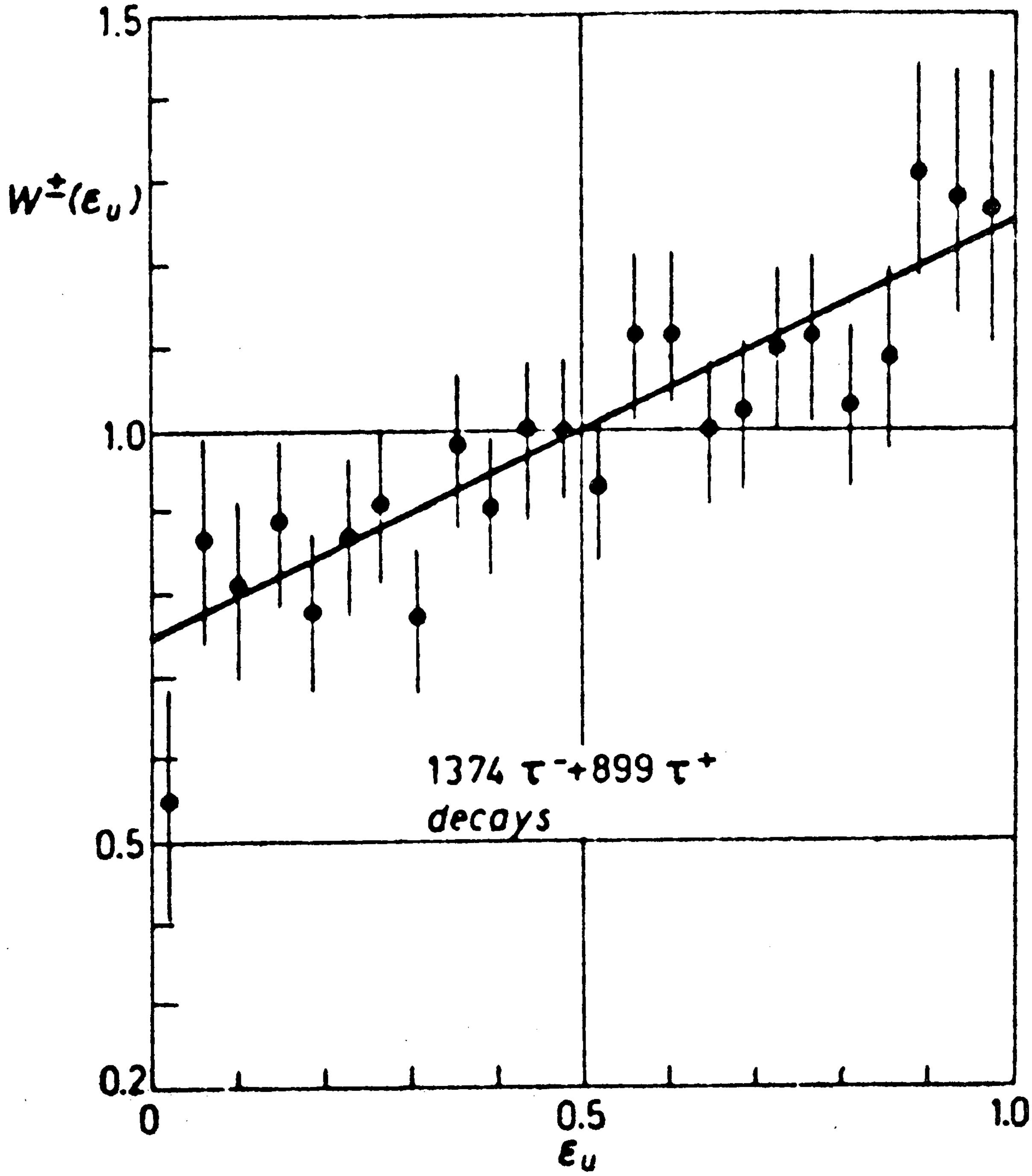


FIG. 1

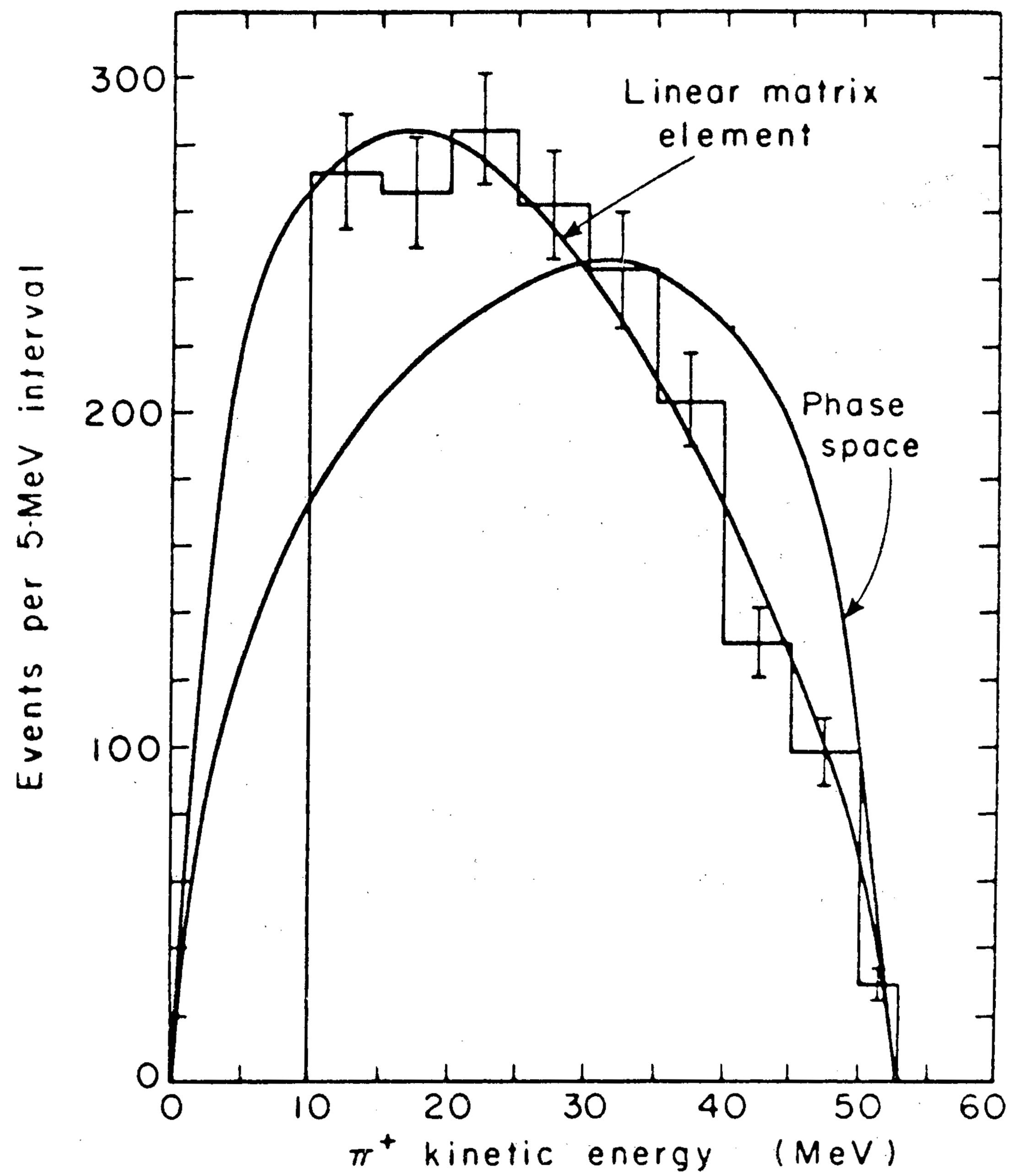
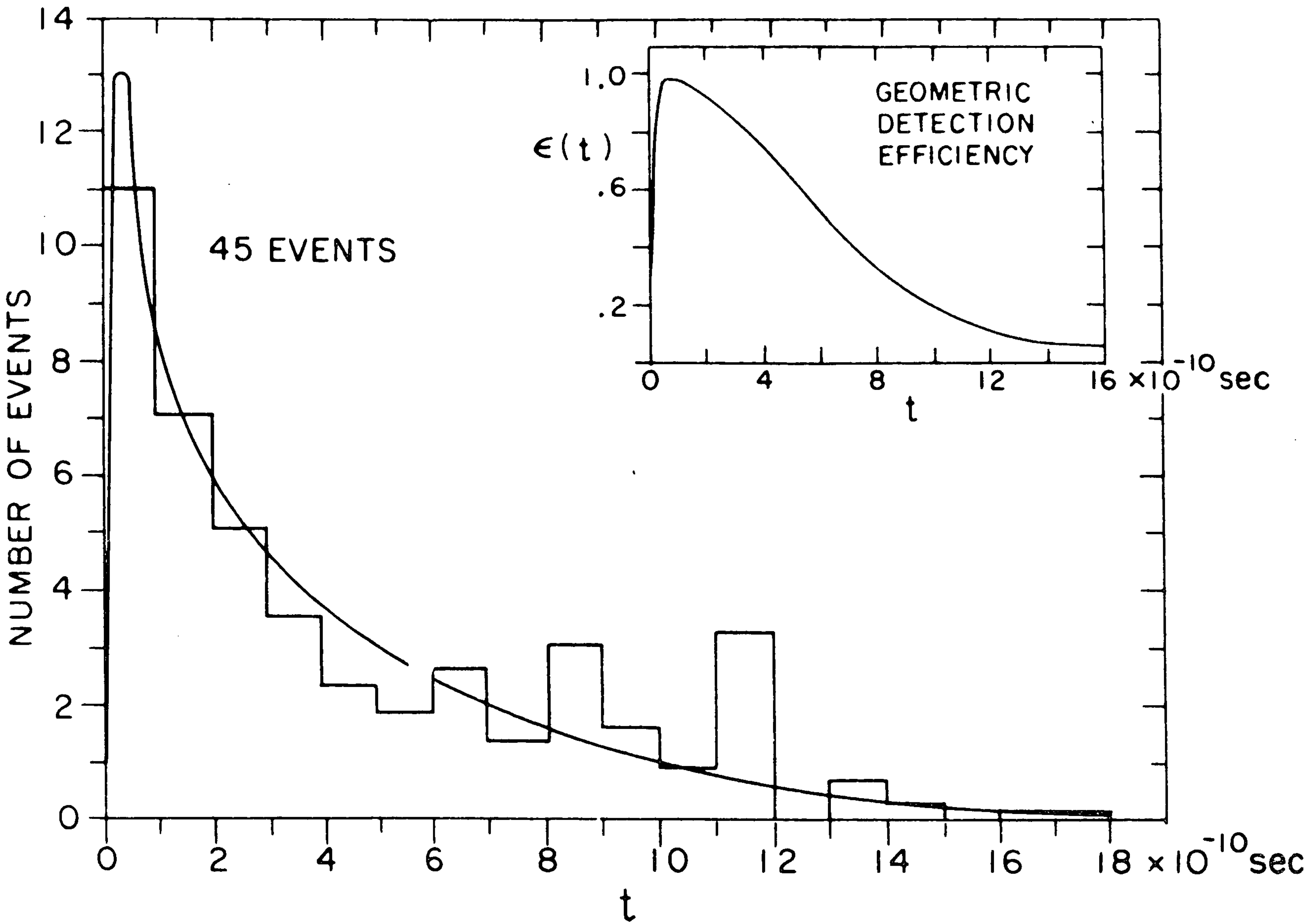

300
200
100
0
Events per 5-MeV interval
Linear matrix element
Phase space
0
10
20
30
40
50
60
π^+ kinetic energy (MeV)

FIG. 2



14
12
10
8
6
4
2
0
NUMBER OF EVENTS
45 EVENTS
0
2
4
6
8
10
12
14
16
18 ×10^{-10} sec
t
1.0
.6
.2
ε(t)
GEOMETRIC
DETECTION
EFFICIENCY
0
4
8
12
16 ×10^{-10} sec
t

FIG. 3

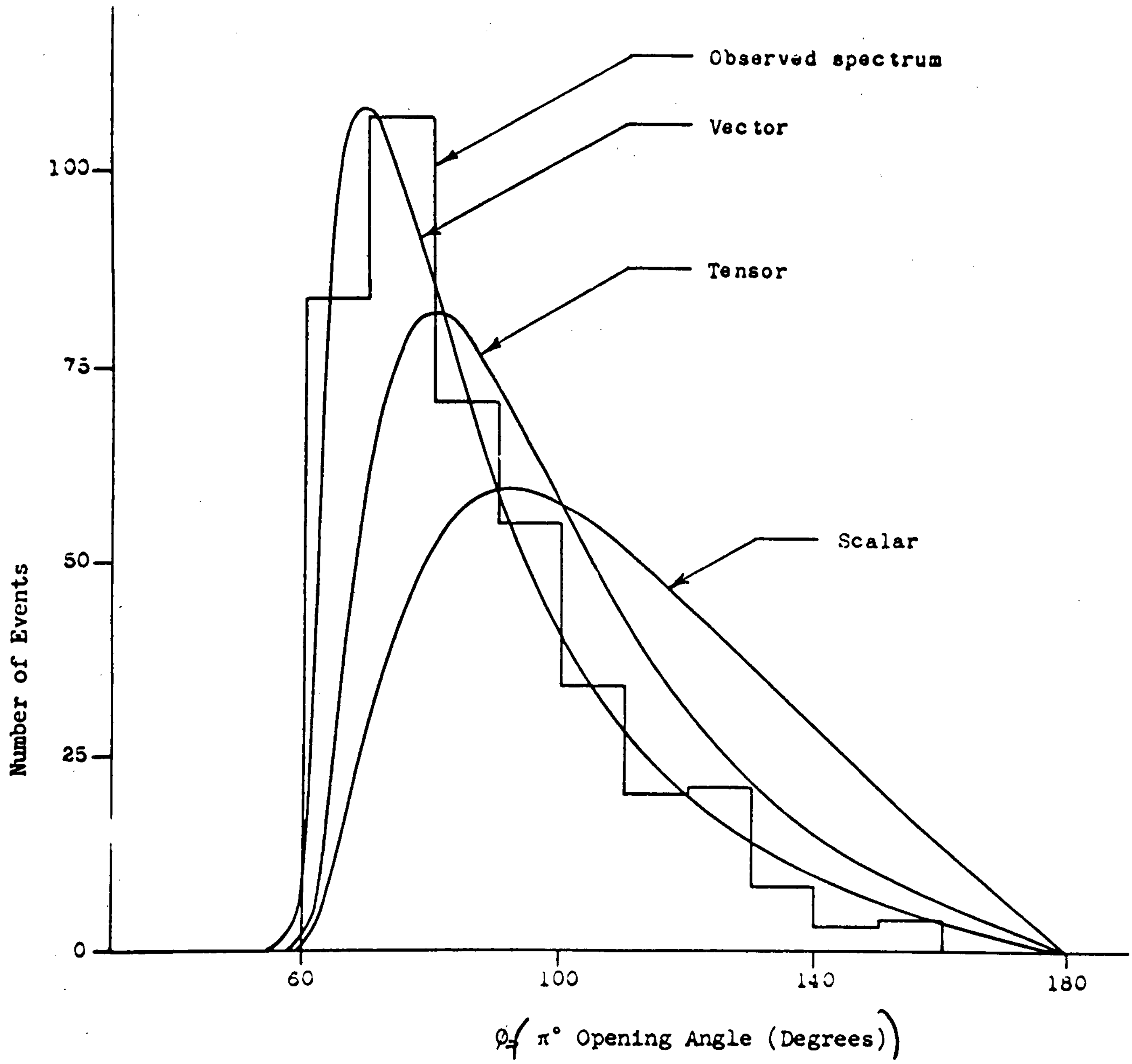

Observed spectrum
Vector
Tensor
Scalar
100
75
50
25
0
Number of Events
60
100
140
180
ϕ (π° Opening Angle (Degrees))

FIG. 4

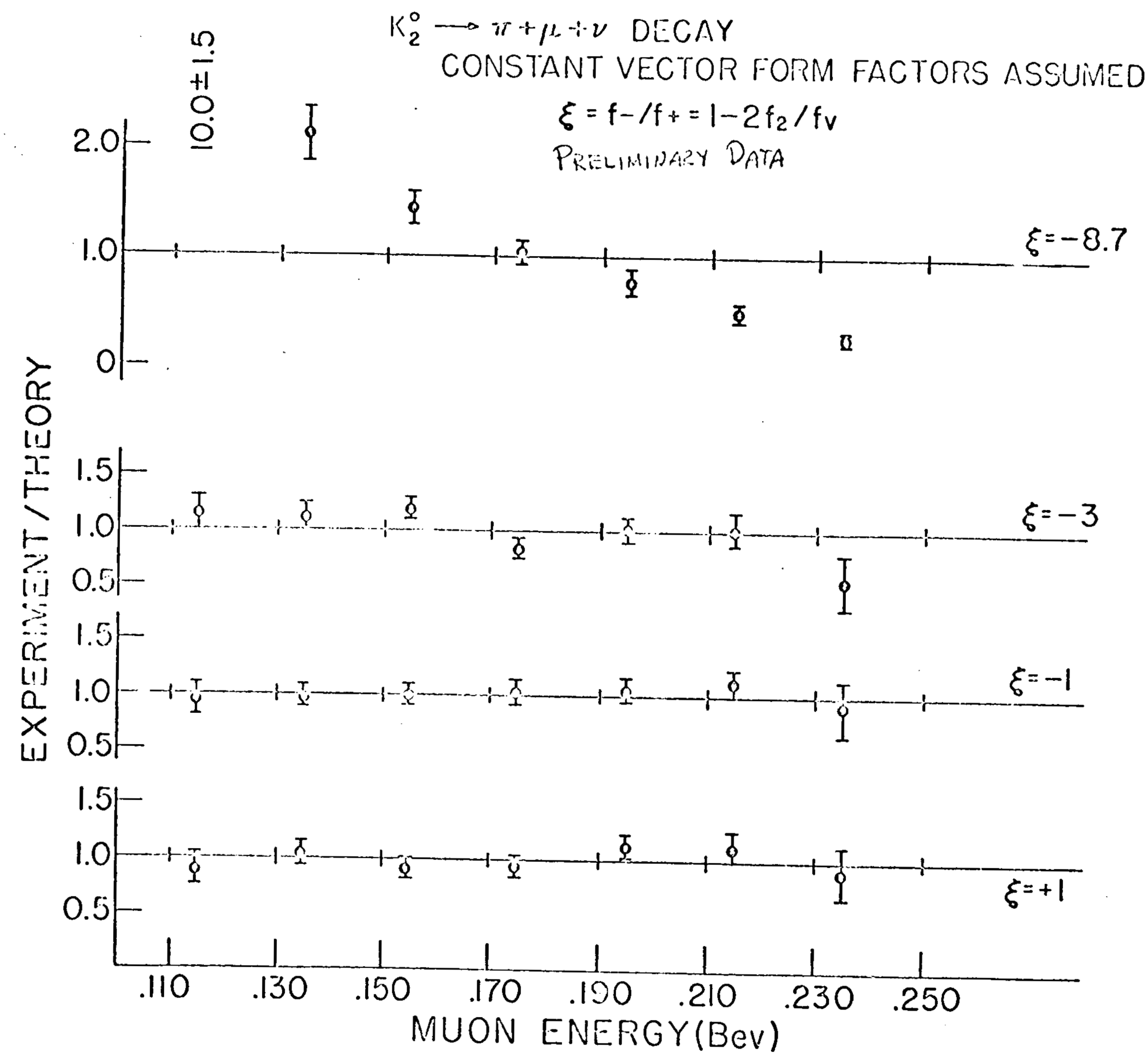
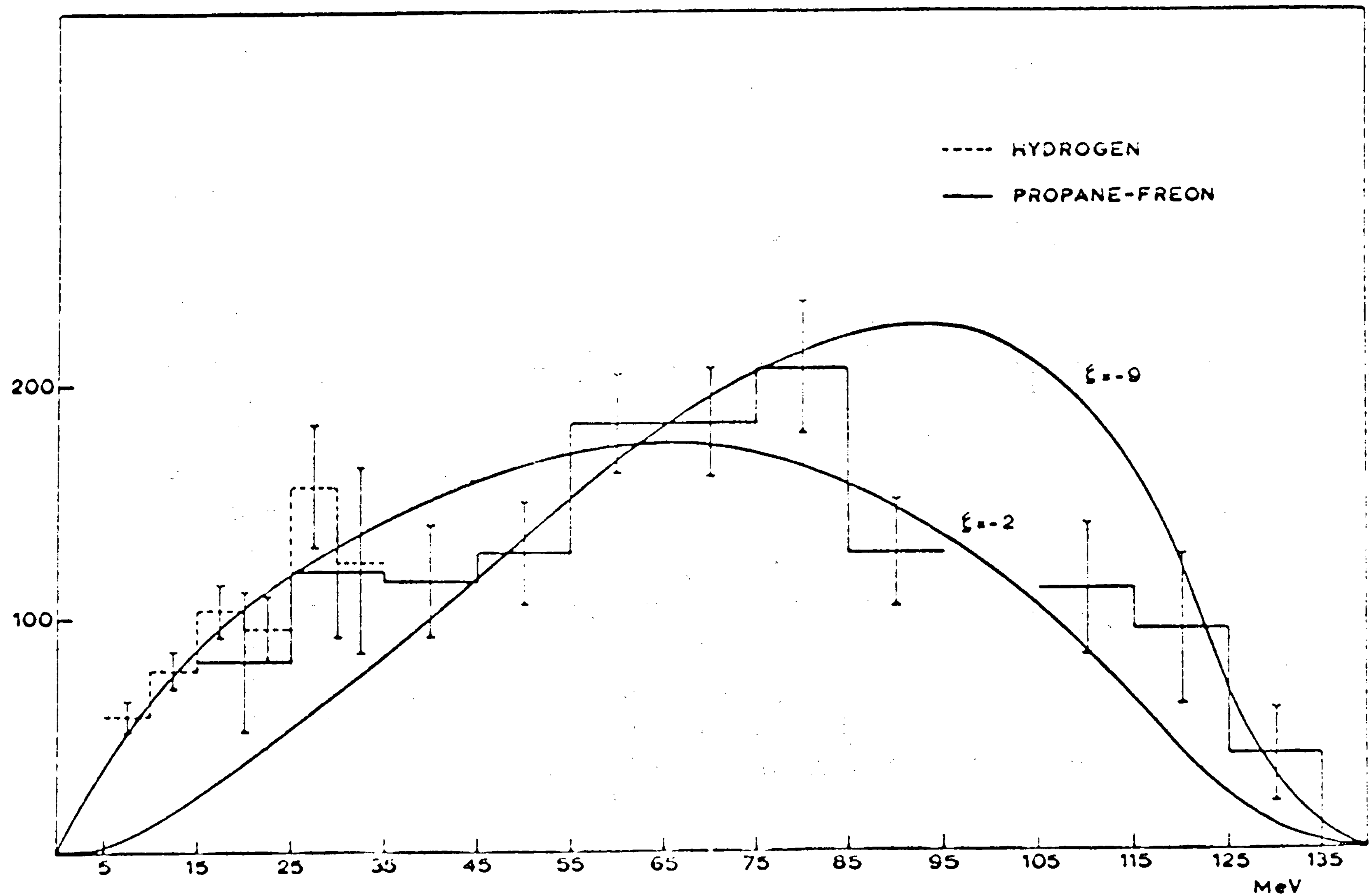
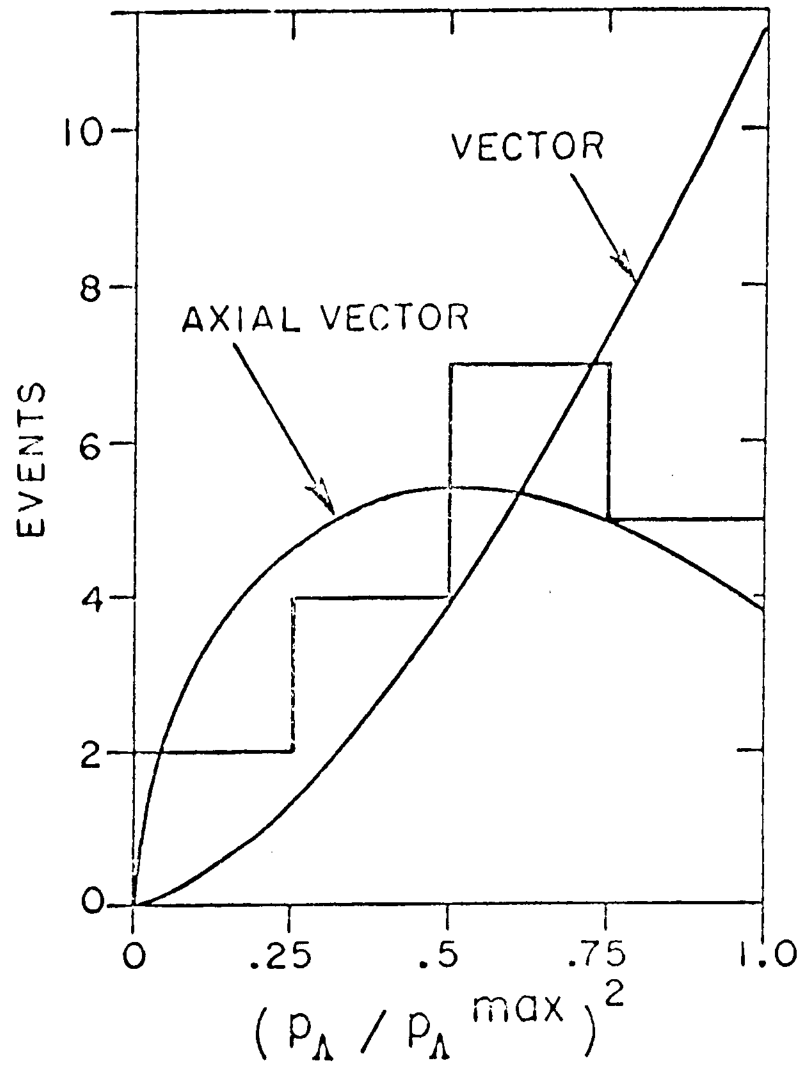

$K_2^\circ \longrightarrow \pi + \mu + \nu$ DECAY
CONSTANT VECTOR FORM FACTORS ASSUMED
$\xi = f_-/f_+ = 1-2f_2/f_v$
PRELIMINARY DATA
10.0±1.5
2.0
1.0
0
1.5
1.0
0.5
1.5
1.0
0.5
1.5
1.0
0.5
$\xi = -8.7$
$\xi = -3$
$\xi = -1$
$\xi = +1$
EXPERIMENT / THEORY
.110
.130
.150
.170
.190
.210
.230
.250
MUON ENERGY (Bev)

FIG. 5



HYDROGEN
PROPANE-FREON
ξ = -9
ξ = -2
200
100
5
15
25
35
45
55
65
75
85
95
105
115
125
135
MeV

FIG. 6



VECTOR
AXIAL VECTOR
EVENTS
10
8
6
4
2
0
0
.25
.5
.75
1.0
(p_Λ / p_Λ max)^2

FIG. 7