WEAK INTERACTIONS OF STRANGE PARTICLES

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I will not attempt to summarize all results that have appeared since the 1960 Rochester Conference. In particular I will omit some subjects which were discussed at the Aix-en-Provence International Conference on Elementary Particles, in September 1961, and for which no new material has been presented to this conference.

In several of the experiments I will discuss, one measures the decay parameters α, β and γ for a parent baryon of spin 1/2 decaying into a daughter baryon of spin 1/2 plus a pion (spin zero). The decays of interest are $\Xi^- \to \Lambda + \pi^-$ (here the Ξ^- spin is not yet proven to be 1/2, as we shall see), $\Lambda \to p + \pi^-$, $\Lambda \to n + \pi^0$, $\Sigma^+ \to n + \pi^+$, $\Sigma^+ \to p + \pi^0$ and $\Sigma^- \to n + \pi^-$.

Let us first review the meaning of the decay parameters, and how they are measured. By angular momentum conservation only the states $S_{\frac{1}{2}}$ and $P_{\frac{1}{2}}$ are available to the daughter baryon and pion. (" Baryon " will always mean spin 1/2, here.) Both states are usually present, i.e. parity is not conserved. If S and P are the complex amplitudes, four real numbers describe the decay. Four is reduced to three when we neglect an overall phase. The usual parameters are

$$\alpha = -2\mathrm{Re}\, S^* P/(|S|^2 + |P|^2)$$

$$\beta = 2\,\mathrm{Im}\, S^* P/(|S|^2 + |P|^2)$$

$$\gamma = (|S|^2 - |P|^2)/(|S|^2 + |P|^2)\,.$$

If T invariance holds, β is zero, except for final state interactions. Notice that α is invariant under the interchange of S and P, so that a measurement of α gives $|S|/|P|$ *or* $|P|/|S|$. To resolve the ambiguity one must measure the sign of γ.

For a parent baryon with 100% polarization along the $+z$ axis, the wave function for the daughter baryon's spin and angles ϑ (polar) and ϕ (azimuth) of emission is given by

$$\Psi = (S + P\cos\vartheta)\uparrow + (Pe^{i\phi}\sin\vartheta)\downarrow\,, \tag{1}$$

so that the decay distribution is given by

$$\frac{dN}{d\cos\vartheta} \sim |\Psi|^2 = |S + P\cos\vartheta|^2 + |\mathrm{P}e^{i\phi}\sin\vartheta|^2$$
$$= (|S|^2 + |P|^2)(1 - \alpha\cos\vartheta)\,. \tag{2}$$

If the parent is not 100% polarized but has polarization p, then in Eq. (2) α becomes αp. Therefore an " up-down " measurement of a decay asymmetry (distribution in ϑ) does not give α, but gives αp. The polarization p depends on the strong process by which the parent baryon is produced. By parity conservation (strong process) the direction of p is always perpendicular to the production plane.

In the experiments I will first describe (Ξ^- decay, by the Brookhaven-Syracuse group [1)], and by the Berkeley [2)]-U.C.L.A. [3)] group; and Λ decay, by Cronin and Overseth [9)]) the experimenters measure α directly, using in each case a parent baryon which is guaranteed to be completely unpolarized. We will now explain how they do this.

The first question is, how do they get unpolarized parents, when we know that in general p is not zero, and in fact is often found to be nearly 1. The answer is that to get " effectively " unpolarized parents they simply throw away information as to the orientation of the production plane. The odd term, $-\alpha p\cos\vartheta$, then averages to zero. This " depolarization " trick works only for spin 1/2. For spin 3/2, for instance, there could be terms in $\cos^2\vartheta$ that would not average to zero.

The next observation is that with an unpolarized source of parent baryons (spin 1/2), the daughter baryon has a longitudinal polarization of $-\alpha$. We can see this easily from Fig. 1. We quantize along the direction of emission of the daughter baryon. The two *equal* populations of spin-up and spin-down parents are at the centre of the diagram. Then, since we are are quantizing along the direction of the linear momentum, the daughter baryon's spin is in the same direction as that of the parent; the orbital angular momentum in the final state is perpendicular to the linear momentum and therefore cannot flip the baryon spin. For a given parent spin we see from Eq. (2) that the number of daughters emitted along the spin is proportional to $(1-\alpha)$ = " along ", and the number against the spin to $(1+\alpha)$ = " against ". From the diagram we then see that for a given direction of emisson the average longitudinal polarization of the daughter is

$$[(\text{along})-(\text{against})]/[(\text{along})+(\text{against})] = -\alpha\,.$$

Next one must measure the longitudinal polarization of the daughter, to measure $-\alpha$ of the parent. For instance, in the decay $\Xi^- \rightarrow \Lambda + \pi^-$, the daughter Λ will as we have just seen have the longitudinal polarization $p_\Lambda = -\alpha_{\Xi^-}$ along its direction of motion (with respect to the Ξ^- rest frame). We therefore look, with respect to this direction, at the decay asymmetry for emission of the proton, in the cases where we observe $\Lambda \rightarrow p + \pi^-$. From Eq. (2) this determines $-\alpha_\Lambda \cdot p_\Lambda = \alpha_\Lambda \alpha_\Xi$. Notice that all Ξ^- decays are useful, and that 2/3 of the Λ decay visibly.

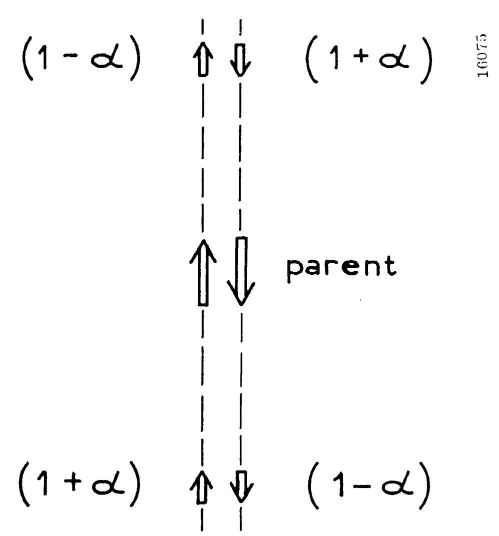

Fig. 1 Longitudinal polarization of daughter from decay of unpolarized parent. The expressions in parenthesis give the decay probabilities.

The experimental situation is much more difficult when one wishes to measure α_Λ, as for example in the spark chamber experiment of Cronin and Overseth. To measure the longitudinal polarization $p_{\text{proton}} = -\alpha_\Lambda$ of the proton in $\Lambda \rightarrow p + \pi^-$, one must scatter the proton, for example from carbon plates, and look for scattering asymmetry. The scattering probability is typically 1/50 compared to the 2/3 for Λ decay in the Ξ^- analysis. Furthermore for the scattering analysis not all Λ decays are useful. One needs decay protons *transversely* polarized in the laboratory frame (where the carbon plates are). For an unpolarized Λ decaying at rest in the laboratory you would have no transversely polarized protons at all. But for the fast Λ's used, the velocity of the Λ with respect to the laboratory is large compared to the velocity of the decay proton with respect to the Λ rest frame, so that for four out of the " six possible directions " ($\pm x$, $\pm y$, $\pm z$) of proton emission with respect to the Λ rest frame, one has transverse polarization in the laboratory frame. This is illustrated in Fig. 2, which is a diagram in velocity space with the addition of arrows to give the spin directions. Since the Λ is unpolarized in the α determination, it has no arrow. Neither does the carbon nucleus. The two proton-emission directions in parenthesis are useless since they give no transverse polarization with respect to the carbon.

The carbon has a large analyzing power, given by the parameter $\langle S \rangle$, which has magnitude about 0.6. The experimenters determine $p_\Lambda \langle S \rangle = -\alpha_\Lambda \langle S \rangle$, from the scattering asymmetry with respect to the plane formed by the three points (in velocity space) of the carbon (lab.), Λ, and proton. The magnitude of $\langle S \rangle$ is independently determined in double-scattering experiments of protons on carbon.

Next we consider how the experimenters measure β. Since β vanishes if T (time reversal) invariance holds

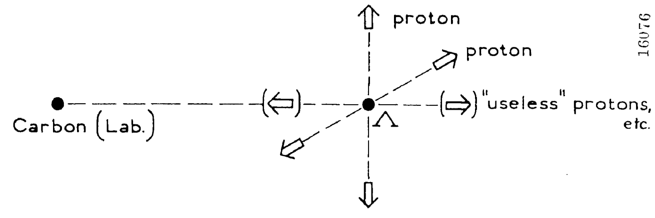

Fig. 2 Velocities and spins of Λ, decay proton and carbon scatterer, in determining α_Λ. The position of a point on the diagram gives the *velocity* of the particle. The arrow gives the spin.

(and if final state interactions are negligible), we look for a suitable polarization which should vanish under T. To do this we will see that we need a polarized parent, and must measure the daughter polarization. The suitable polarization is shown in Fig. 3, which is again a velocity and spin diagram.

If T-invariance holds then the decay in Fig. 3c occurs as frequently as that in Fig. 3a, so that there can be no net polarization of the type of Fig. 3a. Thus the experimenter looks at decays where the daughter is emitted in the production plane of the parent, and looks for a daughter polarization perpendicular to the velocity of the daughter with respect to the parent, and lying in the production plane. In the Ξ^- decay analysis, by means of subsequent Λ decays, four of the " six possible " decay directions are useful. In the Λ decay analysis by subsequent proton-carbon scatters, only two of the six directions are useful.

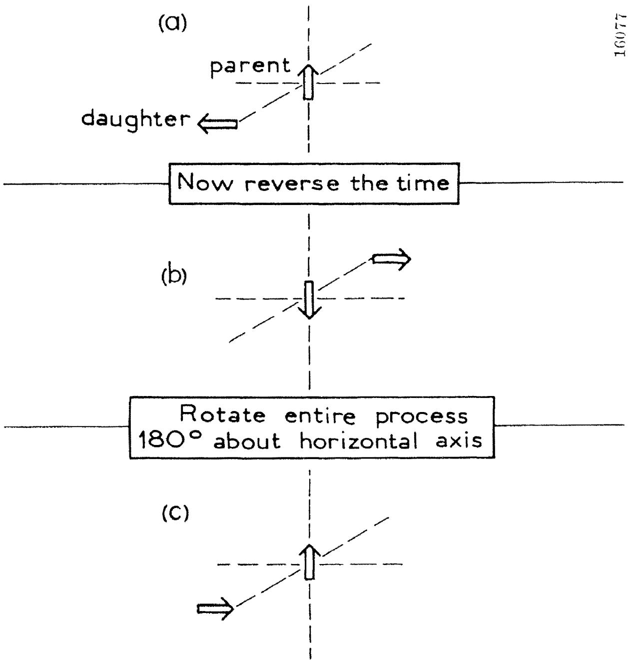

Fig. 3 Behaviour of parent and daughter polarization and velocity under time reversal. The velocities and spins are *both* reversed in going from 3 a to 3 b. The parent velocity is zero. Final-state interactions are neglected.

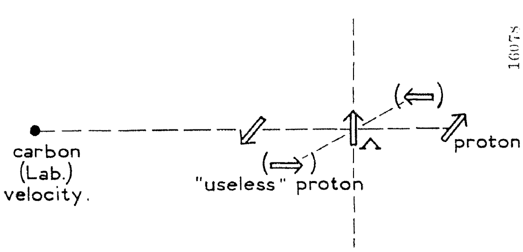

Fig. 4 Scattering analysis of β. (A position on the diagram represents a velocity.)

This is illustrated in Fig. 4, where the useless directions are in parenthesis.

(In this discussion our language is of course over simplified. The various polarizations always vary linearly with the cosine of some appropriate polar angle; our " useless " directions are those where the effect is zero, " useful " where it is maximum. In practice it is important for the experimenter to verify the angular dependences, to check for biases and to use all of the data.)

Next we consider how the experimenters measure γ, to tell whether S oi P predominates. Again we need polarized parents. Consider first pure S-wave in the decay. Then for all directions of emission, the daughter has the same spin direction as the parent, since no orbital angular momentum is available to flip the spin. This is also evident from Eq. (1) if we let $P = 0$. Next consider pure P-wave decay. For decays along the direction of parent polarization, i.e. perpendicular to the production plane, the orbital angular momentum (a.m.) cannot flip the spin, since the orbital a.m. is perpendicular to the linear momentum. For decays in the production plane the spin of the daughter is opposite that of the parent. This is evident from Eq. (1), with $S = 0$, and with $\cos\vartheta = 1$ or 0, respectively. In both the Ξ^--decay and the Λ-decay experiments, " all six directions " are useable. This is illustrated for the Λ analysis in Fig. 5a, b. We see that the two extremes of predominantly S and predomi-

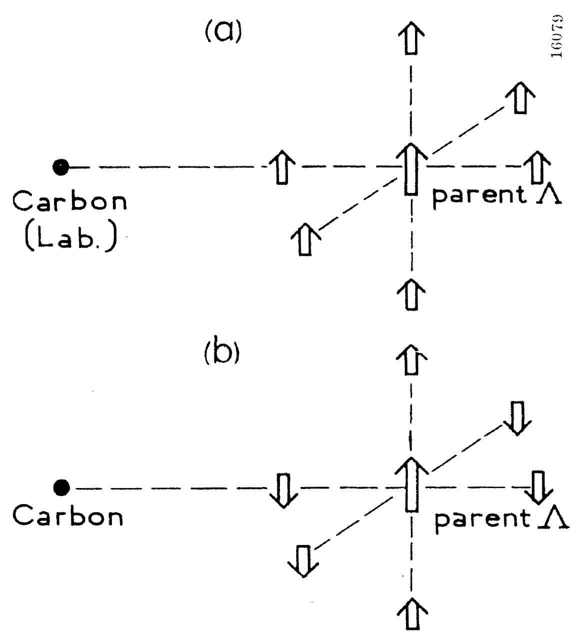

Fig. 5 Polarizations of Λ and proton in pure S-wave and pure P-wave Λ-decay. (A position on the diagram represents a velocity.)

nantly P are easily distinguishable. Eq. (1) shows how the polarization varies for intermediate cases. We turn now to the experiments.

I. $\Xi^- \to \Lambda + \pi^-$

This decay has been studied by a Brookhaven-Syracuse group [1] (" East ") and by a U.C. Berkeley [2], U.C.L.A. [3] group (" California "). The California Ξ^- are produced in the 72″ chamber through the reaction $K^- + p \to \Xi^- + K^+$, with K^- of 1.2 to 1.6 GeV/c (Berkeley) or 1.8 GeV/c (U.C.L.A.). The Eastern Ξ^- are produced in the same reaction, and also in reactions where K^+ is replaced by $K^+ + \pi^0$, or $K^0 + \pi^+$. They use K^- of 2.3 and 2.5 GeV/c. Where possible we will include a comparison with early results of Fowler *et al.* [4].

a) Decay parameters (assuming the Ξ^- spin is ½)

There now seems to be absolutely no doubt that α_Ξ and α_Λ have opposite signs. This fact rules out some theories which predict $\alpha_\Xi = \alpha_\Lambda$, the weak global symmetry models of, for instance, d'Espagnat and Prentki [5], and of Treiman [6].

The value of α_Ξ (fourth column of table) is obtained by dividing $\alpha_\Lambda \alpha_\Xi$ by $\alpha_\Lambda = -0.61 \pm 0.05$, which is the recent value of Cronin and Overseth [9]. We notice that the Calif. avg. value, $\alpha_{\Xi^-} = +0.62 \pm 0.11$, satisfies within the errors the relation $|\alpha_\Xi| = |\alpha_\Lambda|$. This last relation is predicted, for instance, by the doublet approximation [7].

The sign convention for α can be remembered as follows. The fact that α_Λ is negative means that the decay proton likes to be emitted in the direction of the Λ spin. Therefore it likes to be right-handed (positive helicity).

The Calif. avg. value for β_{Ξ^-} (fifth column) differs from zero by 2.5 standard deviations, and is furthermore large in magnitude, if we neglect the large error. If Berkeley's large and positive value for γ_Ξ (last column) is substantiated then it will imply mostly S-state for the final π-Λ system. The Ξ^- mass is only about 60 MeV below the Y_1^* resonance (which has a half width of about 25 MeV). If the Y_1^* spin is 1/2 (not known), and if the Ξ^- spin is really 1/2 (not proven), then a large value of β is presumably easily explained in terms of π-Λ interaction in a final S-state. There are too many " ifs " here, and too little data. We leave this question to the discussion.

TABLE I

Experimenters	No. events	$\alpha_{\Xi^-}\alpha_\Lambda$	α_{Ξ^-}	β_{Ξ^-}	γ_{Ξ^-}
Eastern [1]	75	-0.63 ± 0.20	$+1^{+0}_{-0.35}$		
Berkeley [2]	450	-0.30 ± 0.08	$+0.49 \pm 0.14$	-0.63 ± 0.31	$+0.63 \pm 0.31$
U.C.L.A. [3]	100	-0.52 ± 0.13	$+0.85 \pm 0.23$	-0.85 ± 0.53	—
Calif. avg.	550	-0.38 ± 0.06	$+0.62 \pm 0.11$	-0.68 ± 0.27	—
Fowler *et al.* [4]	18	-0.65 ± 0.35	$+1^{+0}_{-0.55}$	—	—

b) Lifetime and mass of Ξ^-

" Weak Global Symmetry " [6] predicts (weakly?), $\tau_{\Xi^-} = (3/2)\tau_\Lambda$, which becomes $\tau_{\Xi^-} \approx \tau_\Lambda$ after a phase space correction. Since τ_Λ is known to be either 2.8 (" Western value ", see paragraph Xe) or 2.4 (" Eastern value ", ditto remark) $\times 10^{-10}$ sec, the prediction fails.

TABLE II

Experimenters	Mass	Mean life
Brookhaven-Syracuse [1]	1321.0 ± 0.5 MeV	$1.16^{+0.26}_{-0.17} \times 10^{-10}$ sec
Fowler *et al.* [4]	1317.9 ± 1.9 MeV	$1.28^{+0.41}_{-0.25} \times 10^{-10}$ sec

c) Spin of the Ξ^-

Suppose the Ξ^- is strongly polarized (relative to the production plane) in the production process $K^- + p \to \Xi^- + K^+$. Also suppose that the admixture of opposite parities in the decay is large; i.e. comparable amounts of $S_{\frac{1}{2}}$ and $P_{\frac{1}{2}}$ if the spin is 1/2, $P_{\frac{3}{2}}$ and $D_{\frac{3}{2}}$ if the spin is 3/2, etc. Then in the decay $\Xi^- \to \Lambda + \pi^-$ one can obtain a large " up-down " asymmetry in the number of π^- emitted above and below the production plane. (We consider the π^- rather than the Λ, to emphasize that we make no use of the Λ decay.) The largest possible up-down ratio is 3/1, and this can be achieved only for a Ξ^- spin of 1/2, and with maximum parity non-conservation and maximum polarization, namely with, $|\alpha_\Xi| = 1$ and $|p_\Xi| = 1$. The higher the spin, the smaller is the maximum up-down asymmetry. (This is perhaps easily believed from the classical limit of large spin, i.e. a decaying fly-wheel. Polar fragments carry no "useful" angular momentum. Therefore most of the decay fragments are " required " to go off in the equatorial plane in order to conserve angular momentum. At least this is so if the decay is not very exothermic !)

The experimenters find the following values for 3ξ (avg.), where ξ is the cosine of the angle of the decay π^- with respect to the normal to the production plane, and the average is taken over all of the decays.

Experimenters	3ξ (avg.)
Brookhaven-Syracuse [1]	$+0.52 \pm 0.26$
U.C.L.A.[3]	$+0.51 \pm 0.17$

If the spin of the Ξ^- is J, then the magnitude of 3ξ (avg.) must be less than $1/2J$, *provided that the distribution in ξ is linear* [8]. For spin 1/2 this sum is $\alpha_\Xi p_\Xi$. For spin 3/2 the upper limit is 1/3. This is exceeded by 1 std. deviation for the U.C.L.A. data, and by 0.7 std. dev. for the Eastern data. For spin 5/2 the limit is 1/5, exceeded by 1.8 std. dev. by U.C.L.A. and by 1.23 std. dev. by the East.

Of course if the spin is J, the distribution in ξ can go up to ξ^{2J}, so that it is not fair to assume that the distribution is linear. The above test is therefore not strictly valid. A valid test is provided by the Lee-Yang test functions [8]. For spin 3/2 they define $T_{3/2,\,3/2} = 9P_1(\text{avg.}) + 5P_2(\text{avg.}) - (7/3)P_3(\text{avg.})$, which must be less than 1 if the spin is 3/2. If $P_2(\text{avg.}) = P_3(\text{avg.}) = 0$ we get the simpler but invalid (to an experimentalist) test " assuming a linear distribution ". Similar test functions are constructed for higher spins. The Eastern experimenters [1] find

$$T_{\frac{3}{2},\frac{3}{2}} = 1.6 \pm 0.9 > 1\ ?$$

$$T_{\frac{5}{2},\frac{5}{2}} = 3.7 \pm 1.7 > 1\ ?$$

They thus find the spin 3/2 condition violated by $(0.6/0.9) = 0.7$ std. dev., and the spin 5/2 condition violated by $2.7/1.7 = 1.6$ std. dev. Clearly more data are needed, even to rule out spin 5/2.

II. DECAY PARAMETER FOR $\Lambda \to p + \pi^-$

The experiments are listed in inverse chronological order in Table III.

In listing the first three experiments in the table, I have converted the experimenters' published errors, obtained by going down by a factor e^{-1} on a likelihood function, to the more customary values obtained by going down by $e^{-1/2}$; this usually means I divided their errors by $\sqrt{2}$.

TABLE III

Experimenters	Λ-Source	Detector	α	β	γ
Cronin and Overseth [9]	$\pi^- + p$	Spark C.	-0.62 ± 0.05	$+0.19 \pm 0.19$	$+0.78 \pm 0.04$
Gray *et al.*[10]	$K^- + \text{He}$	He B.C.	-0.66 ± 0.25	—	—
Beall *et al.*[11]	$\pi^- + p$	Spark C.	$-0.67^{+0.13}_{-0.17}$	assume = 0	$+0.74^{+0.09}_{-0.23}$
Birge and Fowler [12]	π^-+propane	Propane B.C.	-0.45 ± 0.4	—	—
Boldt *et al.* [13]	π^-+iron	Cloud C.	$+0.85^{+0.15}_{-0.21}$	—	—

We see that α is now fairly well-known. The early sign discrepancy is resolved. The sign of α is opposite to that predicted by application of UFI to Λ decay, by Okubo *et al.* [14]. As to the magnitude, an additional recent result is relevant. This is obtained by measurement of the decay asymmetry as a function of production angle in the reaction $\pi^-+p\to\Lambda+K^0$.

My collaborators and I find that $\alpha p(\vartheta)$ is 0.68 ± 0.07 at its maximum [15]. This is consistent with the value of Cronin and Overseth, if our Λ's are 100% polarized.

The value of β found by Cronin and Overseth is consistent with CP-invariance, taking into account the final state interactions from the known π-p phase shifts [9]. Experimenters with unpolarized sources of Λ's cannot measure β or γ. This explains the vacancies in the table. Beall *et al.* assume $\beta=0$, but this hardly affects at all their results for α and γ.

The above results for γ show that the S-wave dominates in $\Lambda\to p+\pi^-$. This result has been used to show that the spin of ${}_\Lambda H^4$ is 0, and that therefore the $K\Lambda$ and πN parities are probably the same [16].

III. THE DECAY $\Lambda\to n+\pi^0$

If the $\Delta I=1/2$ rule holds for $\Lambda\to$(nucleon+pion), then for the decay amplitudes A we have

$$A(n\pi^0) = -2^{-1/2}A(p\pi^-),$$

so that the decay parameteis α, β and γ should be the same for the two decay modes, and the decay rates should give

$$B_\Lambda \equiv (\Lambda\to p\pi^-)/(\Lambda\to p\pi^-)+(\Lambda\to n\pi^0) = 0.660\,.$$

(This is 2/3, with a small phase space correction.)

One should remember that these same predictions follow if $\Delta I=3/2$ is also present, provided that $\Delta I=3/2$ and 1/2 amplitudes are in the ratio $A_{3/2}=-2\sqrt{2}A_{1/2}$ [14].

a) Decay parameter α

Using counters, Cork *et al.* [17] have measured up-down decay asymmetries for $\Lambda\to p+\pi^-$, and for $\Lambda\to n+\pi^0$. The Λ were produced via

$$\pi^+ + d\to K^+ + \Lambda + p\,.$$

The geometry was the same in the two determinations, so that the polarization of the Λ was the same. Thus they can cancel the factor p_Λ. They find

$\alpha_\Lambda(n\pi^0)/\alpha_\Lambda(p\pi^-)=p_\Lambda\alpha_\Lambda(n\pi^0)/p_\Lambda\alpha_\Lambda(p\pi^-)=+1.10\pm0.27$. This is in agreement with the prediction 1.00 of the $\Delta I=1/2$ rule.

b) Decay parameter γ_0

Determination of α gives S/P or P/S but does not tell whether S or P predominates. No direct measurements of α, β or γ have yet been made for $\Lambda\to n+\pi^0$ because of the difficulty of measuring the scattering asymmetry of the neutrons. By an indirect method, Block *et al.* [18] have determined γ, as follows. They measure R, the decay rate for ${}_\Lambda He^4\to$(all π^0 modes) divided by the decay rate for ${}_\Lambda He^4\to$(all π^- modes), and find $R=2.28\pm0.43$. The spin of ${}_\Lambda He^4$ is believed to be zero [18]. The decays ${}_\Lambda He^4\to$(all π^0 modes) are calculated by Dalitz and Liu [19] to be mostly via the mode ${}_\Lambda He^4\to\pi^0+He^4$. This mode goes *only* through S-wave (for spin zero ${}_\Lambda He^4$). Thus the numerator of R is very sensitive to the ratio S_0/P_0 for $\Lambda\to n+\pi^0$.

Using the known branching ratio $\Gamma(n\pi^0)/\Gamma(p\pi^-)$ for free Λ decay, and the known [11] S/P ratio for $\Lambda\to p+\pi^-$, they obtain the formula [19]

$$R = 2.51-2.06P_0^2/(S_0^2+P_0^2) \equiv 1.48+1.03\gamma_0\,.$$

Their result for R gives $P_0^2/(S_0^2+P_0^2)=0.11^{+0.21}_{-0.11}$, which is equivalent to $\gamma_0=+0.78^{+0.22}_{-0.42}$. They thus favour predominance of S-wave in $\Lambda\to n+\pi^0$.

c) Branching ratio B_Λ

Our result is the only new value ieported [15]. We find $B_\Lambda=0.685\pm0.017$, by counting the charged decays.

For comparison we list values from the 1960 Rochester Conference [20]

$B_\Lambda=0.72\pm0.08$ Baglin *et al.* (counts neutrals).
$B_\Lambda=0.65\pm0.05$ Columbia group (counts charged).
$B_\Lambda=0.63\pm0.03$ Crawford *et al.* [21] (counts charged).
$B_\Lambda=0.65\pm0.05$ Brown *et al.* (counts neutrals).

There is no serious disagreement among experimenters, nor with the value 0.660 predicted by the $\Delta I=1/2$ rule.

IV. $\Sigma\to n+\pi$ DECAYS AND THE $\Delta I=½$ RULE

a) $\Sigma^+\to p+\pi^0$ decay parameter α_0

This has been measured by observing the scattering asymmetry of the decay proton in a spark chamber, by Beall *et al.* [11]. They obtain $\alpha_0 = +0.78^{+0.08}_{-0.09}$. (This agrees with theories involving Global Symmetry, or Doublet Approximation, which predict $\alpha_0 = -\alpha_\Lambda$. See, for instance, Refs. [5, 6, 7]. The Σ^+ were produced by 1.23 GeV/c π^+ in the reaction

$$\pi^+ + p \rightarrow \Sigma^+ + K^+ .$$

The Σ^+ polarization was *small*, so that β_0 and γ_0 were not measurable.

b) $\Sigma^+ \rightarrow n + \pi^+$ decay parameter α_+

Cork *et al.*[17] have measured both Σ^+ decay asymmetries in the same geometry, in a counter experiment, and obtained $\alpha_+ \bar{p}_{\Sigma^+} = 0.03 \pm 0.08$, $\alpha_0 \bar{p}_{\Sigma^+} = +0.75 \pm 0.17$. Since the Σ^+ polarization is the same in each case, they can take the ratio, cancelling $\bar{p}_{\Sigma^+}$, to obtain α_+/α_0. Multiplying by the measured value [11] of α_0 they get $\alpha_+ = +0.03 \pm 0.08$. The reaction was

$$\pi^+ + p \rightarrow \Sigma^+ + K^+ ,$$

as in case *a*, but at a lower momentum, 1.13 GeV/c. The polarization was large.

c) $\Sigma^- \rightarrow n + \pi^-$ decay parameter α_-

This quantity has resisted measurement via up-down asymmetry because of uncertainty as to the polarization of the Σ^-. Franzini *et al.* [22] found $\alpha_- \bar{p}_{\Sigma^-} = 0.01 \pm 0.17$, from Σ^- produced by π^- of 1.23 GeV/c, in the reaction $\pi^- + d \rightarrow \Sigma^- + K^0 + p$. The idea is to hope the impulse approximation works, so that this reaction is essentially $\pi^- + n \rightarrow \Sigma^- + K^0$, and then to use charge symmetry to say that the Σ^- polarization is the same as in $\pi^+ + p \rightarrow \Sigma^+ + K^+$ at the same momentum. The trouble is that Beall *et al.* [11] and also Baltay *et al.* [23] find small Σ^+ polarization if any, at 1.23 GeV/c, for $\pi^+ + p \rightarrow \Sigma^+ + K^+$.

Recently Tripp, Watson and Ferro-Luzzi [24] have discovered a $K^- p$ resonance with mass 1520 MeV, in the state $D_{3/2}$, $I = 0$. The outgoing channels are about 60% $\Sigma\pi$. Thus the Σ^- and Σ^+ have the same polarization. They find a large Σ^+ decay asymmetry and thus a large $\Sigma^\pm$ polarization. They then find $\alpha_- = +0.16 \pm 0.21$ [25].

Another determination of α_- has been recently obtained by Nussbaum *et al.* [26] using film from the 72″ deuterium chamber associated-production run. They studied the reactions

$$\pi^+ + d \rightarrow a(+) = \Sigma^+ + K^+ + n, \text{ and}$$
$$b(+) = \Sigma^+ + K^0 + p,$$

and the corresponding charge-symmetric (CS) reactions

$$\pi^- + d \rightarrow a(-) = \Sigma^- + K^0 + p, \text{ and}$$
$$b(-) = \Sigma^- + K^+ + n,$$

using pions of 1.19 GeV/c.

Their preliminary results are

$$\alpha_0 \bar{p}_{\Sigma^+} = \begin{cases} +0.61 \pm 0.29 & \text{for } a(+) \\ -0.52 \pm 0.41 & \text{for } b(+) \end{cases}$$

$$\alpha_- \bar{p}_{\Sigma^-} = \begin{cases} +0.27 \pm 0.22 & \text{for } a(-) \\ +0.17 \pm 0.16 & \text{for } b(-) \end{cases}$$

Since CS guarantees $\bar{p}_{\Sigma^+} = \bar{p}_{\Sigma^-}$ for *a*, and also for *b*, we can divide and obtain

$$\alpha_-/\alpha_0 = \begin{cases} +0.44 \pm 0.40 & \text{for } a(\pm) \\ -0.33 \pm 0.43 & \text{for } b(\pm) \end{cases}$$

which average to $\alpha_-/\alpha_0 = +0.05 \pm 0.30$; or, using the known value [11] of α_0, we get $\alpha_- = +0.04 \pm 0.23$.

d) Consequences for the $\Delta I = \frac{1}{2}$ rule

The triangle relationship [27] that follows from the $\Delta I = 1/2$ rule is, in the notation of Gell-Mann and Rosenfeld [27], $\sqrt{2}\mathbf{N}_0 + \mathbf{N}_+ = \mathbf{N}_-$, with $\mathbf{N} = \mathbf{S} + \mathbf{P}$. The vectors $\mathbf{N}$ are real, by *T*-invariance, and since the final state phase shifts are small [27]. Therefore they can be represented as vectors in the *S-P* plane. The magnitudes of the vectors are determined from the three decay rates, which are almost exactly equal [27, 28], within the errors. Using α_0, α_+ and α_- from Ref. [11, 17, 25], Tripp *et al.* construct Fig. 6. The triangle relationship is not well satisfied, for either choice for the *S-P* ambiguity. The inconsistency with the $\Delta I = 1/2$ rule is between two and three standard deviations, for the " closest " choice.

If we average the value for α_- of Nussbaum *et al.*[26] with that of Tripp *et al.* [25] we find $\alpha_- = +0.10 \pm 0.16$. This will slightly increase the discrepancy with $\Delta I = 1/2$, by reducing the " 5° " of $\mathbf{N}_-$ in Fig. 6, to 3°.

It is clearly extremely important to determine the decay parameters α_+, α_- and especially α_0 with greater accuracy. Even more informative would be the determination of γ_+, γ_- and γ_0, to give the S/P ratios. From Fig. 6, the " worst " possibility would correspond to more than 3 std. deviations against $\Delta I = 1/2$. Of course if the $\Delta I = 1/2$ rule does not hold, it is even possible for $\Sigma^+ \to n + \pi^+$ and $\Sigma^- \to n + \pi^-$ to *both* be pure S-wave, or both pure P-wave.

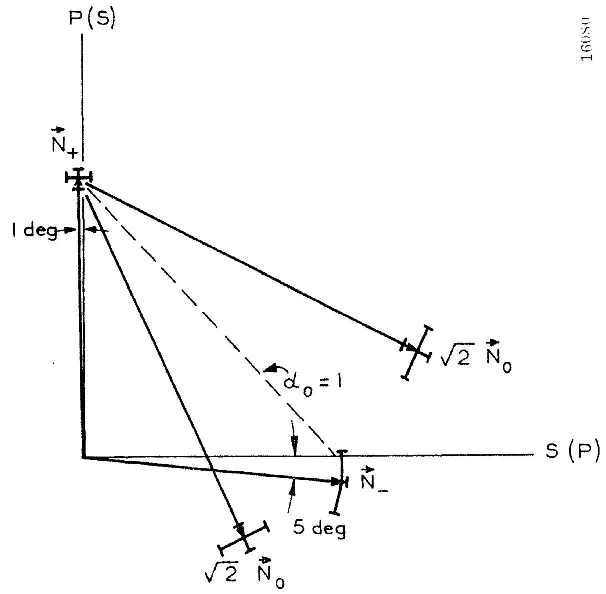

Fig. 6 Possible failure of the $\Delta I = \frac{1}{2}$ rule in Σ-decay. The two representations of the amplitude N_0 correspond to the present ambiguity for the S/P ratios in the three decays.

V. LEPTONIC (L) DECAYS OF STRANGE PARTICLES AND THE RULES $\Delta I = \frac{1}{2}$ (L-DECAYS), AND $\Delta S = \Delta Q$

The following table lists ΔS, ΔQ, $|\Delta I|$, and $|\Delta I_z|$ for the strongly interacting particles, in the decays to be discussed. L will stand for either a muon or an electron. The notation will not distinguish between various kinds of neutrinos.

a) The decay $\Sigma^+ \to n + \mu^+ + \nu$

A clear-cut example of this decay has very recently been found by Galtieri *et al.* [29]. It satisfies $\Delta S/\Delta Q = -1$. All of the suggested interpretations alternative to the muonic decay have been shown to be exceedingly unlikely. Only the " philosophical " argument " There is only one event " remains.

b) Three body leptonic decays of K_1^0 and K_2^0

(a) $\Delta I = {}^1/_2$ rule and $K_2^0 \to \pi^\pm + L^\mp + \nu$

The absolute rate for K_2^0 decaying into e^+, e^-, μ^+ and μ^- has been measured by Alexander, Almeida, and Crawford [30, 31]. They sum over all four decay modes, and obtain the total L decay rate

$$\Gamma_2(L^\pm) = (9.31 \pm 2.49) \times 10^6 \text{ sec}^{-1}.$$

According to the $\Delta I = 1/2$ rule,

$$\Gamma_2(L^\pm) = 2\Gamma_{K^+}(\pi^0 L^+ \nu) = (16.5 \pm 1.18) \times 10^6 \text{ sec}^{-1}.$$

The discrepancy between the measurement and the prediction gives 50/1 odds agains $\Delta I = 1/2$. It implies that one or both of (3/2, 1/2) and (3/2, 3/2) are present.

(b) $\Delta S = \Delta Q$ rule and $\Gamma_1/\Gamma_2 = \dfrac{\Gamma(K_1^0 \to \pi^\pm L^\mp \nu)}{\Gamma(K_2^0 \to \pi^\pm L^\mp \nu)}$

If (3/2, 3/2) is absent, i.e. if $\Delta S = -\Delta Q$ is absent, one has the prediction $\Gamma_1(L^\pm) = \Gamma_2(\Gamma^\pm)$ for $L = \mu$ or e. Ely *et al.* [32] have been the first to suggest that the $\Delta S = \Delta Q$ rule fails. They find

$$\Gamma_1(e^\pm)/\Gamma_2(e^\pm) = 11.9^{+7.5}_{-5.6}.$$

TABLE IV

Decay	ΔS	ΔQ	$\Delta S/\Delta Q$	$(\lvert\Delta I\rvert, \lvert\Delta I_z\rvert)$
$\Sigma^- \to n + L^- + \nu$	+1	+1	+1	$({}^1/_2, {}^1/_2)$ or $({}^3/_2, {}^1/_2)$
$\Sigma^+ \to n + L^+ + \nu$	+1	−1	−1	$({}^3/_2, {}^3/_2)$ only
$K^+ \to \pi^0 + L^+ + \nu$	−1	−1	+1	$({}^1/_2, {}^1/_2)$ or $({}^3/_2, {}^1/_2)$
$K^0 \to \pi^- + L^+ + \nu$	−1	−1	+1	$({}^1/_2, {}^1/_2)$ or $({}^3/_2, {}^1/_2)$
$K^0 \to \pi^+ + L^- + \nu$	−1	+1	−1	$({}^3/_2, {}^3/_2)$ only
$\bar{K}^0 \to \pi^+ + L^- + \nu$	+1	+1	+1	$({}^1/_2, {}^1/_2)$ or $({}^3/_2, {}^1/_2)$
$\bar{K}^0 \to \pi^- + L^+ + \nu$	+1	−1	−1	$({}^3/_2, {}^3/_2)$ only

Alexander, Almeida and Crawford [30, 31] find

$$\Gamma_1(L^\pm)/\Gamma_2(L^\pm) = 6.6^{+6.0}_{-4.0} .$$

In an earlier experiment, Crawford *et al.* [33] found

$$\Gamma_1(L^\pm)/\Gamma_2(L^\pm) = 3.5^{+3.9}_{-2.7} .$$

(No priority claim ! This result was, and is, consistent with unity, and was so taken.) This same experiment [33] gives $\Gamma_2(L^\pm) = (8.5 \pm 2.8) \times 10^6 \ \mathrm{sec}^{-1}$ if one assumes $\Gamma_1 = 9\Gamma_2$. It gives instead

$$\Gamma_2(L^\pm) = (20.4^{+7.2}_{-5.6}) \times 10^6 \ \mathrm{sec}^{-1}$$

if one assumes $\Gamma_1 = \Gamma_2$. [The absolute value $\Gamma_2(L^\pm)$ obtained by Alexander *et al.* [30, 31] does not depend on Γ_1/Γ_2.]

The conclusion is that the $\Delta S = \Delta Q$ rule is probably wrong.

VI. THE $\Delta I = \frac{1}{2}$ RULE AND NON-LEPTONIC K DECAYS

a) $K_2^0 \to \pi^+ + \pi^- + \pi^0 \equiv (+-0)$

From the $\Delta I = 1/2$ rule one predicts [34)] $\Gamma_2(+-0) = 1.032 \times 2\Gamma_+(+00) = (2.87 \pm 0.23) \times 10^6 \ \mathrm{sec}^{-1}$ (See Ref. [30] for numbers.) Alexander, Almeida, and Crawford [30, 31] find

$$\Gamma_2(+-0) = (2.66 \pm 1.34) \times 10^6 \ \mathrm{sec}^{-1} ,$$

in good agreement, but based on only 4 events. If instead we use the branching ratio $\Gamma_2(+-0)/\Gamma_2$ (all charged) of Luers *et al.* [35] [which is based on 55 decays into $(+-0)$], together with our absolute rate for $\Gamma_2(L^\pm)$ we find [30, 31] $\Gamma_2(+-0) = (1.44 \pm 0.43) \times 10^6 \ \mathrm{sec}^{-1}$, which is smaller than the prediction by a factor of 2; it is 2.95 std. deviations down from the prediction of the $\Delta I = 1/2$ rule, and corresponds to about 100/1 odds.

b) $K_2^0 \to \pi^0 + \pi^0 + \pi^0 \equiv (000)$

From the $\Delta I = 1/2$ rule one predicts [34]

$$\Gamma_2(000) = \Gamma_+(++-) - \Gamma_+(+00) .$$

With phase space corrections and known K^+ rates this prediction becomes

$$\Gamma_2(000) = 1.565\Gamma_+(++-) - 1.255\Gamma_+(+00) = (5.55 \pm 0.27) \times 10^6 \ \mathrm{sec}^{-1} .$$

Anikina *et al.* [36] have reported at this conference the branching ratio $\Gamma_2(000)/\Gamma_2$ (all charged) $= 0.38 \pm 0.07$. If we combine their result with the absolute rate $\Gamma_2(L^\pm)$ of Alexander *et al.* [30] we find [31]

$$\Gamma_2(000) = (4.09 \pm 1.38) \times 10^6 \ \mathrm{sec}^{-1} .$$

This result is just 1 std. deviation below the prediction, $5.55 \times 10^6 \ \mathrm{sec}^{-1}$, of the $\Delta I = 1/2$ rule. To compare Anikina *et al.* [36] and Luers *et al.* [35] directly, we combine the two formulas of Sawyer and Wali [34], phase space and the measured K^+ branching ratios to obtain the prediction of the $\Delta I = 1/2$ rule (independent of the admixture of the three possible $I = 1$ states),

$$\Gamma_2(000)/\Gamma_2(+-0) = (1/2)(++-)/(+00) - 1/2 \to 0.76(++-)/(+00) - 0.61 = 1.94 \pm 0.21 .$$

The combined experiments give for this ratio the value $0.38/0.134 = 2.83 \pm 0.64$, which is 1.3 standard deviations above the prediction.

In summary, from Luers *et al.* and Anikina *et al.* there is a 1.3 std. dev. discrepancy with $\Delta I = 1/2$; from Anikina *et al.* and Alexander *et al.* there is 1 std. dev.: these " add ", so that with Luers *et al.* and Alexander *et al.* there is a 2.95 std. dev. disagreement with the $\Delta I = 1/2$ rule.

c) K_1^0 branching ratio $B(K)$

The $\Delta I = 1/2$ rule predicts

$$B(K_1^0) = \Gamma(K_1^0 \to 2\pi^0)/\Gamma(K_1^0) = 1/3 .$$

If one allows enough $\Delta I = 3/2$ to account for the existence of $K^+ \to \pi^+ + \pi^0$ then $B(K_1^0)$ should lie between 0.29 and 0.38 [27]. Three new determinations have been reported at the conference; that of Chretien *et al.* [37], using a heavy-liquid bubble chamber; that of Brown *et al.* [38] using a xenon bubble chamber; and our value from the associated production experiment in the 72″ hydrogen chamber [15]. For comparison we then list the values reported at the 1960 Rochester Conference [20] in Table V.

No experiment disagrees with the prediction of $\Delta I = 1/2$, except possibly that of Anderson *et al.* [15], whose value lies 1.2 std. dev. below the supposed lower limit for the prediction. The disagreement between Anderson *et al.* and the (present) value of Brown *et al.* amounts to 2.5 std. dev.

TABLE V

$B(K_1^0)$	Experimenters and method		
0.294 ± 0.021	Chretien *et al.*[37)	Count neutrals.	
0.329 ± 0.013	Brown *et al.*[38)	Count neutrals.	
0.260 ± 0.024	Anderson *et al.*[15).	Count charged.	
0.32 ± 0.04	Crawford *et al.*[21)	10″ H.B.C.	Count charged
0.30 ± 0.04	Brown *et al.*	Xenon.	Count neutral
0.30 ± 0.08	Columbia.	H.B.C.	Count charged
0.26 ± 0.06	Baglin *et al.*		Count neutrals

VII. THREE-BODY LEPTONIC *K*-DECAY SPECTRA AND *V—A* THEORY

The decays are $K \to \pi + L + \nu$. $K = K_2^0$ or K^+, and $L = e$ or μ.

Only one of V and A (or S and P) can be present, so the spectra have only the (pure) possibilities S, V and T.

From the two four vectors of the K and π one can form one scalar, two vectors (themselves, or linear combinations), and one tensor. Correspondingly there is one scalar form factor f_S, two vector form factors f_V and g_V, and one tensor form factor f_T. When L is an electron the part of the spectrum containing g_V becomes unmeasurably small for kinematic reasons. When L is a muon f_V and g_V are both important.

a) $K_2^0 \to \pi^\pm + e^\mp + \nu$ spectrum

Luers *et al.*[35) find from their Dalitz plot of K_2^0 decays in the Brookhaven 20″ H.B.C. that (a) T does not fit; (b) either S or V fits if the form factors are allowed to be strongly energy dependent; (c) only V fits if the form factors are taken to be constant. V fits well.

b) $K^+ \to \pi^0 + e^+ + \nu$ spectrum

Brown *et al.* [39), using a xenon B.C. find (a) T does not fit; (b) either S or V fits if the form factors can be strongly energy dependent; (c) only V fits for constant form factors, and it fits well.

c) Branching ratio $\Gamma_+(\pi^0 \mu^+ \nu)/\Gamma_+(\pi^0 e^+ \nu)$

Roe *et al.* [40) find 0.96 ± 0.16 for this ratio. (Xenon B.C.) Suppose now that the theory is really V. (Test later.) The e^+ spectrum depends only on $f_V(e^+)$, since the term in $g_V(e^+)$ is negligible. Assume universality. This means $f_V(e^+) = f_V(\mu^+)$. Then the branching ratio depends only on $g_V(\mu^+)/f_V(\mu^+)$. There are two solutions, $g_V(\mu)/f_V(\mu) = +0.5 \pm 0.4$ and -4.8 ± 0.4, that will give the observed branching ratio. These two solutions predict different spectra for $K^+ \to \pi^0 + \mu^+ + \nu$. Theorists much prefer the solution 0.5 (see L. B. Okun's Rapporteur discussion p. 843).

d) $K^+ \to \pi^0 + \mu^+ + \nu$ spectrum

Dobbs *et al.* [41), have looked at the muon energy spectrum above 50 MeV, using a filamentary chamber plus image intensifier. They use emulsion data to normalize the counting rate below 50 MeV. They find that the spectrum corresponds to

$$g_V(\mu)/f_V(\mu) = -4.8 ,$$

and not at all to $+0.5$.

Brown *et al.* (xenon) have now looked at their spectrum [42). They find, under the assumption of constant form factors (which is compatible with their data) (a) S does not fit; (b) T is poor but can fit (10% χ^2 probability); (c) V fits well with

$$g_V(\mu)/f_V(\mu) = +0.5 ,$$

and poorly with -4.8. They therefore disagree completely with Dobbs *et al.* [41). The theorists are on their side. Brown *et al.* also analyze their data so as to simultaneously determine $f_V(e)$, $f_V(\mu)$ and $g_V(\mu)$ from the e^+ rate, the μ^+ rate, and the μ^+ spectrum, *without* making any a priori assumption of universality. They find $f_V(\mu)/f_V(e) = 1.09 \pm 0.15$, in excellent agreement with universality. The spectrum can be seen in their paper [42).

The conclusion is that the *V-A* theory works here.

VIII. LEPTONIC DECAYS OF HYPERONS

a) Humphrey *et al.*[43] have searched hard for muonic hyperon decays, and summarize the world's denominators, to construct a table which we repeat here. The numerators are easy to summarize—one decay $\Lambda \to p+\mu^- +\nu$ of Eisler *et al.*[44], and one decay $\Sigma^+ \to n+\mu^+ +\nu$ of Galtieri *et al.*[29], in violation of the $\Delta S = +\Delta Q$ rule. The same authors have previously[45] summarized electronic hyperonic decay rates, and these are included in their table, with one exception. That is the branching ratio

$$R = \Gamma(\Lambda \to p+e^- +\bar{\nu})/\Gamma(\Lambda) = (0.85\pm 0.3)\times 10^{-3}$$

reported to this conference by Ely *et al.*[46]. Their value of R is based on 120 events. The error represents uncertainties in detection efficiency (heavy liquid B.C.). All rates are down by roughly a factor of 10 from the predictions of Feynman and Gell-Mann.

b) Decay $\Sigma^- \to \Lambda + e^- + \nu$

Grimellini *et al.*[47] report the first unambiguous case, in the helium B.C. The " denominator " is not yet known.

IX. K^- AND K^+ BRANCHING RATIOS

a) Becker *et al.*[48] have measured K^- branching ratios, using K^- decaying in flight in the helium B.C. Their results agree with emulsion experiments, but

TABLE VI

Hyperon Muonic Decays

Branching fractions, f(%)	$\Sigma^-\mu^-$	$\Sigma^+\mu^+$	$\Lambda\mu^-$	Electronic decay values [a] (Listed for comparison)		
				Σ^-e^-	Σ^+e^+	Λe^-
1. Predicted by Feynman and Gell-Mann [b], f_{FGM}	2.5	1.01 [c]	0.3	5.6	2.3 [c]	1.6
2. Experimental, published to date, f_{exp}	<0.2 [d]	0.3 [d, e]	0.1 [d, f]		see row (5)	
3. $f(\mu)$ expected by scaling $f(e)$ data proportionally to phase space . . .	0.05	0.04	0.04			
4. $f(\mu)$ reported in this note	0.065	0.15	0.05			
5. All available data [g]	<0.05	0.1	0.03	0.1 [h]	<0.1	0.2 [h]
Detection efficiency (%)						
6. By scanning only	19	19×2 [i]	$30\times\frac{3}{2}$ [j]	28	2×28	. . .
7. On measured events	20	20×2 [i]	$40\times\frac{3}{2}$ [j]	33	2×33	70

[a] See reference [2].
[b] See references [1, 7].
[c] From phase space. However, $\Sigma^+\mu^+$ and Σ^+e^+ decays were formerly believed to be forbidden by the $\Delta S = \Delta Q$ rule.
[d] Survey by D. A. Glaser, in the Proceedings of the Ninth Annual Conference on High-Energy Physics, Kiev, 1959 (Academy of Sciences, Moscow, 1960), p. 260.
[e] Barbaro-Galtieri *et al.*[4]
[f] Eisler *et al.* See reference [4].
[g] These fractions represent only the samples known to us, and especially examined for muonic decays. In *other experiments* comparable numbers of hyperons have been found. Since no uniform procedures were used, efficiencies for finding such events are hard to evaluate, so these experiments were not included in this summary.
[h] In addition to the Σ^-e^- and Λe^- events reported in (2), Bhowmik *et al.* report one Σ^-e^- and two Λe^+ events in a small sample of hyperon decays (Nuovo cimento *21*, 567 and 1066 (1961).
[i] The factor 2 is due to the $\Sigma^+ \to p+\pi^0$ decay mode which will not be confused with $\Sigma^+ \to n+\mu^+ +\nu$.
[j] The factor 3/2 corrects for the neutral decay mode of the normal Λ decay.

when they average their results with emulsion results and compare the grand average with the xenon results of Roe *et al.* [40], they find several std. dev. discrepancy in the subdivision between K_{μ_2} and K_{π_2}. We reproduce the table of Becker *et al.* The column " present exp. " is the helium B.C. result [48]. All of the other experiments summarized in this table are also summarized in Ref. [40].

b) It is very important, in trying to understand the reported violation [30] of the $\Delta I = 1/2$ rule for $K \to \pi + L + \nu$, and for $K \to 3\pi$ (discussed in the para. V and VI), to notice that as far as the *3-body* *K*-decay modes are concerned, all of the experiments are in good agreement, with the exception of Birge *et al.* In calculating [30] the predictions of the $\Delta I = 1/2$ rule, we arbitrarily omitted the results of Birge *et al.*

TABLE VII

K^- and K^+ decay branching ratios

Decay mode	Branching ratios (%)					
	Present experiment	Emulsion experiments			Average emulsions +this exp.	Xenon chamber Roe *et al.*
		Birge *et al.*	Alexander *et al.*	Taylor *et al.*		
K_{μ_2}	56.8±3.5	58.5±3.0	56.9±2.6	—	57.4±2.0	64.2±1.3
K_{π_2}	25.8±3.0	27.7±2.7	23.2±2.2	—	25.6±1.5	18.6±0.9
$K_{\mu_3}+Ke_3+\tau$	11.8±2.0	8.1±2.0	13.2±2.0	—	11.0±1.0	11.5±0.3
τ	5.7±0.9	5.6±0.4	6.8±0.4	5.2±0.3	5.7±0.2	5.7±0.3

X. LIFETIMES

a) K_2^0 lifetime

(a) Combining the leptonic absolute rate of Alexander, Almeida and Crawford [30], the $\pi^+\pi^-\pi^0$ branching ratio of Luers *et al.* [35] and the $\pi^0\pi^0\pi^0$ branching ratio of Anikina *et al.* [36] we calculate [31] a total rate and so obtain a lifetime $\tau_2 = (6.8^{+2.6}_{-1.5}) \times 10^{-8}$ sec.

(b) By comparison, Bardon *et al.* [49] obtained long ago $\tau_2 = (8.1^{+3.3}_{-2.4}) \times 10^{-8}$ sec, by attenuation with distance.

(c) Darmon *et al.* [50], with a heavy liquid B.C. and 15 events = 24 events minus 9 events-calculated-background find $\tau_2 = (5.1^{+2.4}_{-1.3}) \times 10^{-8}$ sec.

b) ${}_{\Lambda}H^4$ lifetime

Crayton *et al.* [51] using a Bevatron K^- beam and an emulsion stack, find $\tau({}_{\Lambda}H^4) = (1.2^{+0.7}_{-0.3}) \times 10^{-10}$ sec as an upper limit.

c) ${}_{\Lambda}H^3$ lifetime

Block *et al.* [52], from 41 events produced by K^- in the helium B.C. obtain $\tau({}_{\Lambda}H^3) = (1.23^{+0.31}_{-0.20}) \times 10^{-10}$ sec. Dalitz and Rajasekharan point out that this lifetime depends on the spin J of ${}_{\Lambda}H^3$. Block *et al.* use their formulas to calculate $\tau(J=1/2) = 1.78 \pm 0.06$, $\tau(J=3/2) = (2.41 \pm 0.02) \times 10^{-10}$ sec. They normalize to the free $-\Lambda$ lifetime of Block *et al.*, which is $(2.34 \pm 0.06) \times 10^{-10}$ sec. Clearly the spin J of ${}_{\Lambda}H^3$ cannot yet be decided.

d) K_1^0 lifetime

Two recent lifetimes are those of Golden *et al.* [53] from the associated production run, and of Garfinkel [54]. We list the older (and longer) values for comparison, using the table in Garfinkel's thesis [54].

TABLE VIII

$\tau\ (K_1^0)$ in 10^{-10} sec	Experimenters		
0.885 ± 0.025	Golden *et al.*[58]	Berkeley	72″ H.B.C.
$0.90\ \pm 0.05$	Garfinkel [54]	Columbia	20″ H.B.C.
$1.06\ {}^{+0.08}_{-0.06}$	Eisler *et al.*	Columbia	
$1.15\ {}^{+0.40}_{-0.25}$	Blemenfeld *et al.*	Columbia	
$0.84\ {}^{+0.35}_{-0.19}$	Cooper *et al.*	Jungfraujoch	
$0.81\ {}^{+0.23}_{-0.15}$	Brown *et al.*	Michigan	
$1.07\ \pm 0.13$	Boldt *et al.*	MIT	
$0.94\ \pm 0.05$	Crawford *et al.*	Berkeley	10″ H.B.C.

e) Λ-lifetime

There is at present an East-West effect. This is shown in the ideogram (Fig. 7). It does not go with long versus short chambers, at least in the West. We obtain the same values with 10″, 15″ and 72″ chambers. We also sometimes obtain shorter mean lives than is customary elsewhere (see above K_1^0 lifetimes).

We have not yet been able to discover what is wrong with the Eastern Λ lifetimes.

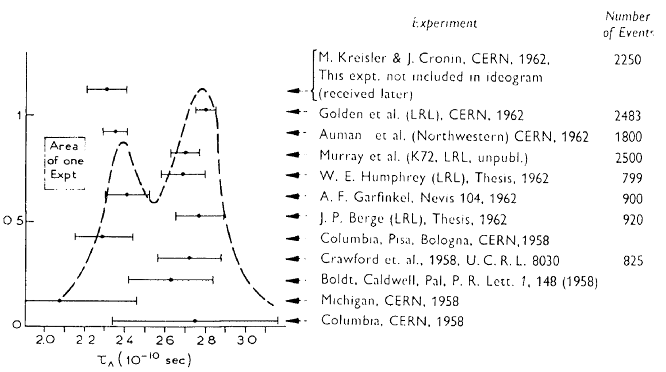

Fig. 7 Ideogram of 14 experiments on the mean life of Λ.

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DISCUSSION

Capps: It is not surprising if the β parameter for cascade decay is not very small. Let me assume that the cascade is spin ½ so that it is the $j = 1/2$ phase shifts that we are concerned with. We have been conditioned by our knowledge that the π-nucleon $j = 1/2$ phase shifts are small to expect this in other pion-baryon systems. It is pretty clear now that the pion-Σ S wave phase shifts are not all small. So there is no reason to expect that the pion-Λ S wave phase shift should be small.

Roberts A.: Does the disagreement in the number of K_2^0 non-leptonic decays observed by Crawford *et al.*, depend on a knowledge of the K_2^0 lifetime?

CRAWFORD: No. Or rather only to the extent of knowing that the mean decay distance for K_2^0 is about 50 times larger than our fiducial volume, so the K_2^0 decay rate is nearly constant for us.

SACHS: I would like to remark on the experimental bias in the $\Delta S/\Delta Q$ experiment. In reference to my own bias, first I must admit to taking some pleasure from seeing the beginning of the discovery of an unexpected result since, after all, unexpected results are the touchstone of progress in physics. However, all theorists agree that the simplest and most reasonable assumption is $\Delta S = \Delta Q$ and, in fact, Treiman and I used this rule in our first discussion of the leptonic asymmetry experiment. The prejudice of the theorists has been conveyed to the experimentalists who therefore eliminated from their data any apparent leptonic event which could be assigned to any other decay mode, even if the assignment was rather far fetched. Since information on the kinematics is not very good for decays occurring in short times, just the K_1^0 events are eliminated by this procedure so a strong bias in favour of $\Delta S = \Delta Q$ is introduced. Nevertheless, the results strongly indicate $\Delta S \neq \Delta Q$ and I suspect, in view of the bias, that the result is more certain than shown by the statistics.

STEINER: Could you comment on the present status of the various leptonic decay rates of the hyperons and how these rates compare to theoretical predictions.

CRAWFORD: These results can be found in my paper. The rates are all down by the familiar factor of 10 or 20 from the predictions.

WEINBERG: I would like to make two comments referring to possible future experiments:

(1) As Wolfenstein said, the theoretical $p\mu p$ absorption rate assumes absorption to occur in the ortho-state only. I believe one of the experimental groups has found a slight anomalous decrease in counting rate, which could represent a slow ortho to para conversion. If this were the case, and if it were possible to analyze the decay curve to obtain the ratio of ortho and para absorption rates, then a good test of the $V-A$ theory would be available. For $V-A$ (but not $V+A$) the ratio would be almost precisely 3.

(2) I understand that some experimentalists wonder whether it would be worthwhile to study the decay modes $\Sigma^{\pm} \to \Lambda + e^{\pm} + \nu$. This would be very valuable, for an appreciable inequality between the rates of these two modes would force us to a radical revision of our ideas about the structure of the weak interaction currents.

CRAWFORD: Block *et al.* have reported one event of Σ^- decaying into Λ. They cannot yet give a rate. (Leitner made a remark in session W2 (see p. 459) that an upper limit to the $\Sigma^- \to \Lambda$ rate can be obtained from the world data, and this agrees with UFI.)

SNOW: This is a question to Crawford. With respect to the high rate of $(\Gamma_{K_1^0}/\Gamma_{K_2^0})$ for three-body decays, how does one evaluate the bias of the computer programme for having a few events with large χ^2 for a particular hypothesis even though the event is physically really due to that hypothesis. In particular how many of your short time K^0 three-body leptonic decays might conceivably be $K_1^0 \to \pi^+ + \pi^-$ decays with a very large χ^2.

CRAWFORD: We spent a lot of time worrying about this, and as a matter of fact when we measure the K_1^0 to K_2^0 ratio, we have to put in some cut-offs. There are several hundred times more K_1^0 decays than K_2^0 decays in the first few K_1^0 mean lives.

The largest source of contamination is a single Coulomb scatter of one of the decaying pions, and the second largest source of contamination is a small-angle $\pi \to \mu$ decay. We get rid of both of these completely by doing a missing mass calculation on each of the decay charged tracks in the K^0 decay. If you assume it is a K_1^0 decay, then each of the secondaries has the mass of the pion. You can calculate the missing mass for each one, and if you find the pion mass you throw the event out. Notice that this cut-off gets rid of *all* $K_1^0 \to \pi^+ + \pi^-$ followed by any " anomaly " in just one of the pion tracks. Now, since the number of such cut-off events is (a) small (7 events) and (b) agrees with the number calculated for Coulomb scattering, we believe that the number of K_1^0 with *both* tracks anomalous is negligible. Another sort of contamination is the $\pi^0 + \pi^0$ decay with one of the π^0 producing a Dalitz pair. These events we throw out with a well-known type of cut-off on the effective mass of the electron-positron pair. So we believe we do not have any K_1^0 contamination. Also there is a very large gap in the χ^2 between a good K_1^0 and a K_1^0 interpretation of a K_2^0 decay. The smallest kind of a χ^2 that a K_2^0 ever gets is about 60 when you analyse it as a K_1^0, when all our K_1^0's have a χ^2 of less than 25.

SAKURAI: Now that the non-identity of the ν_μ and ν_e has been established, I would like to know the best upper limit on the mass of ν_μ.

LEDERMAN: The upper limit on the mass of the neutrino associated with muons can be obtained by a revision of the discussion given by Barkas, Birnbaum and Smith in Phys. Rev. *101*, 778 (1956). Using the new muon mass and Barkas' analysis one finds as an upper limit for the muon-neutrino mass 7 electron masses. The most sensitive element is the mesic x-ray mass-limit of the pion which must be reduced to improve the result. This is, of course, an important and difficult problem.

LEITNER: Concerning the question of final state interactions in Ξ^- decays, I would like to point out that we have tried to estimate the $\Lambda\pi$ phase shift using both the global symmetry model and the $\bar{K}N$ bound state models for the Y^*, assuming the Ξ^- spin is ½. We find $\delta \approx 10^0$ for the global symmetry model and $\leqslant 30°$ for the $\bar{K}N$ bound state model. It is hard to see how such a small value of the phase shift can account for the apparently large value of β. In fact, since the Ξ mass is 60 MeV from Y^* mass, and because the latter's half width is only 25 MeV, it is difficult to see how any sensible model can give a large phase shift and, incidentally, this strongly supports the hypothesis that charge conjugation invariance is violated in Ξ^- decay.

TELEGDI (question to Wolfenstein): I understand that the better He^3 radius leads to the $He^3 \to H^3$ rate (1400 ± 150) sec^{-1} you listed. What is the dependence of this rate on the magnitude of the induced pseudoscalar coupling? This is not well-known, though the asymmetry of neutrons from μ capture tells us that the PS coupling is large and of the correct sign.

WOLFENSTEIN: The change in that rate was due to the new He^3 radius. In this calculation the usual assumption of a conserved vector current and the pseudoscalar being eight times the axial vector is included. What one has in capture in He^3 is simply $3G_{GT}^2 + G_F^2$ and the contribution of the pseudoscalar is to decrease the rate from what it would be without a pseudoscalar by about 20%. Does that answer the question?

TELEGDI: Yes, it does.

MARSHAK: In connection with the capture of μ^- by He^3 it should be pointed out that H^3 is not the only final state. Actually Yano at Rochester has computed the $n+d$ final state and seems to find about 20% of the H^3. Unless the calculation for H^3 was the partial rate, one has to watch this 20% effect. In fact, it would also be interesting to look for the $n+d$ process.

WOLFENSTEIN: I discussed only the partial rate. The experiment only sees tritons. The calculation of the partial rate is easier than the total rate because one knows the ft-value of the triton decay. Calculations by Primakoff show that about 50% of the captures go to unbound $n+d$ or $2n+p$ states. It would be interesting to see also such processes.

MUKHIN: What is at present the accuracy in the theoretical evaluation of muon capture rate in liquid hydrogen?

WOLFENSTEIN: As far as liquid hydrogen is concerned, there are two questions. One is the molecular question: that is, how well the wave function of the molecule can be calculated, and about the ortho to para transitions. I do not know how good those calculations are. There are also uncertainties due to what you choose for the axial vector coupling constant. This may make an uncertainty of about 5%-10%.

MUKHIN: What is your opinion about the experimental determination of the mean square-root radius for $He^3 \rightarrow H^3$ transition making use of the Panofsky ratio in H and He^3? This is the question in connection with the muon capture rate in He^3 reported by Sulya'ev.

WOLFENSTEIN: There are some theoretical approximations involved in evaluating in such a way the radius which may not make as clear cut a result as the electron scattering result.

RUBBIA: I would simply like to point out that the muon capture experiment in liquid hydrogen is quite sensitive to the pseudoscalar term. Assuming that the axial vector and vector parts are the same here as in β decay, one gets from the CERN and Chicago results a value 13 ± 4 times the axial vector constant for the pseudoscalar term.

I have a second comment about the lifetime of the meso-atom (μp) in the liquid hydrogen. Here also at CERN the lifetime has been determined and the value 0.5 ± 0.2 μs was found, which corresponds to formation of a ($p\mu p$) molecule in 70% of the cases.

TICHO: I would like to remark that preliminary estimates of γ for Ξ decay, based on the UCLA sample of ΞK events, yield a positive value, in agreement with the Berkeley results.

BREIT: My question is related to the one before last. The value of $\overline{r^2}$ obtained from Hofstadter has to do with the charge distribution, irrespective of whether it originates in pions or nucleons. If the β-ray theory phenomena had to do with exactly the same aspects of He^3, there would be no question. But since the charged pions may matter for μ capture differently from the way they affect electron scattering, I wonder whether Wolfenstein could explain just what he did.

WOLFENSTEIN: I should say it does not make a great deal of difference at first. I did subtract the proton radius in the standard way in deriving the radius of He^3 from the Hofstadter results. There are, though, a number of questions which do need to be considered before one directly applies Hofstadter data: for instance, there is a different radius for charge and magnetic distributions, and one has to argue which one one has to use.

BREIT: But is it known just how to make the correction? Did you use the sum of squares, as some people do?

WOLFENSTEIN: This was what I did; I am not sure exactly how it should be done.

DZELEPOV: If you take into account the interaction between l and s in the ($p\mu p$) molecule, there will be a mixture of $1/2$ and $3/2$ states. Which is the relative weight of these two states?

WOLFENSTEIN: Calculations at Columbia show that the spin of the molecule is $1/2$. If the total spin is $3/2$, then the capture rate is much less, because of the hyperfine effect.