MUONIC DECAYS OF Σ AND Λ HYPERONS (*)

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(presented by A. H. Rosenfeld)

I. INTRODUCTION

The purpose of this note is to compile information on the branching fraction for the processes

$$\Sigma^{\pm} \rightarrow \mu^{\pm} \pm \nu + n$$

and

$$\Lambda \rightarrow \mu^{-} + \nu + p \, .$$

Present values of the branching fractions are summarized in Table I. The theoretical fractions f_{FGM} in row 1 were calculated in 1957 by Feynman and Gell-Mann [1].

However, since 1957 the experimental branching fractions for *electronic* decay modes of the hyperons

TABLE I

Hyperon Muonic Decays

				Electronic decay values [1] (Listed for comparison)		
BRANCHING FRACTIONS, f (%)	$\Sigma^-\mu^-$	$\Sigma^+\mu^+$	$\Lambda\mu^-$	Σ^-e^-	Σ^+e^+	Λe^-
1. Predicted by Feyman and Gell-Mann [2], f_{FGM}	2.5	1.01 [3]	0.3	5.6	2.3 [3]	1.6
2. Experimental, published to date, f_{exp}	<0.2 [4]	0.3 [4] [5]	0.1 [4] [6]	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 [7]	<0.05	0.1	0.03	0.1 [8]	<0.1	0.2 [8]
DETECTION EFFICIENCY (%)						
6. By scanning only	19	19×2 [9]	30×3/2 [10]	28	2×28	—
7. On measured events	20	20×2 [9]	40×3/2 [10]	33	2×33	70

[1] See reference 2,
[2] See references 1 and 7.
[3] From phase space. However, $\Sigma^+\mu^+$ and Σ^+e^+ decays were formerly believed to be forbidden by the $\Delta S = \Delta Q$ rule.
[4] 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.
[5] Barbaro-Galtieri *et al.*[4]
[6] Eisler *et al.*[3]
[7] 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.
[8] 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).
[9] The factor 2 is due to the $\Sigma^+ \rightarrow p + \pi^0$ decay mode which will not be confused with $\Sigma^+ \rightarrow n + \mu^+ + \nu$.
[10] The factor 3/2 corrects for the neutral decay mode of the normal Λ decay.

(*) Work done under the auspices of the U.S. Atomic Energy Commission.

have proven to be lower than the f_{FGM} by a factor of 10 or more [2]. In the absence of a generally accepted theoretical explanation for the low absolute rate of hyperon leptonic decay, it still seems reasonable to assume, with Feynman and Gell-Mann, that the ratio $\frac{Y \rightarrow N+\mu+\nu}{Y \rightarrow N+e+\nu}$ is proportional to their phase-space ratio. Muonic decay branching fractions, based on this assumption, are listed in row 3 of the table.

In experiments involving low-energy K^- mesons in the Lawrence Radiation Laboratory 15-inch hydrogen bubble chamber [2], we have examined a selected sample of 8000 Σ^-, 1800 Σ^+, and 4200 Λ hyperons for muonic decays. We found no such events. However, one $\Lambda\mu$ decay has been reported by Eisler *et al.* [3] and a $\Sigma^+\mu^+$ decay is being reported at this conference by Barbaro-Galtieri *et al.* [4].

II. Σ-MUONIC DECAY

The general technique used for μ-decay detection was to scan for low-momentum decay products of Σ. The procedure has already been described in detail [5], but will be summarized briefly.

Normal Σ^- decay ($\Sigma^- \rightarrow \pi^- + n$) produces pions with a pion momentum of about 192 MeV/c in the Σ^- rest frame. Since the muon spectrum from $\Sigma^-\mu^-$ ranges from 0 through 208 MeV/c, we must look for decay tracks of low momentum (slightly lower momenta apply for Σ^+). The momentum ceiling must be chosen to ensure that the probability of the events being a genuine muonic decay is much larger than the probability of its being background. We chose the cut-off momentum $p_c = 80$ MeV/c.

The sources of background in order of decreasing importance are:

(1) Single and plural scattering of the π^-. In our earlier work on a sample of 750 selected Σ^-, we chose $p_c = 100$ MeV/c and calculated a probability $\omega(p_c) \approx 0.05\%$ that normal pions would scatter so much in their direction of curvature so as to appear to have $p < p_c$. In this larger sample of 8000 selected Σ^- we can reduce $\omega(p_c)$ to $<0.006\%$ by choosing $p_c = 80$ MeV/c.

(2) Low-momentum π^- from the radiative process $\Sigma^- \rightarrow \pi^- + N + \gamma$. The pion momentum spectrum has been calculated explicitly [6]. Although the calculations are to some extent dependent on the model, they indicate that the fraction of radiative decay pions below 100 MeV/c should be $0.04\% \approx$ of all Σ decays. This effect should be reduced by a factor of approx. 2, if 80 MeV/c is chosen as the cut-off.

(3) The remaining source of background comes from the production of low-momentum secondary muons for the chain $\Sigma^\pm \rightarrow \pi^\pm + n$, followed by $\pi^\pm \rightarrow \mu^\pm \pm \nu$ decay within several millimeters and or backwards in the π centre of mass. The K-capture reaction $K^- + p \rightarrow \Sigma^\pm + \pi^\pm$ yields a Σ with a momentum of about 180 MeV/c. Therefore, when the Σ decays in flight, the decay pion can have a laboratory-system momentum ranging from 159 through 224 MeV/c. Then, if a $\pi \rightarrow \mu$ decay occurs close to its origin, the decay μ will have a spectrum that extends down to 80 MeV/c. Further, the *a priori* rate of this chain is comparable to the observed limit of Σ muonic decay.

As a result of the above considerations we chose 80 MeV/c as the detection cut-off. The fraction of phase space below this value available for $\Sigma^\pm \rightarrow \mu^\pm$ decay at rest is about 1/5. This fraction is insensitive to Σ momenta below 200 MeV/c.

The data from two different experiments, one run in 1958, the other in 1961, yielded no muonic candidates with $p_\mu \leqq 80$ MeV/c.

There were 1400 $\Sigma^- \rightarrow \pi^- + n$, and 300 $\Sigma^+ \rightarrow \pi^+ + n$ in the 1958 experiment. All these events have now been measured and analyzed, so the efficiency for finding candidates was nearly 100%. In the 1961 experiment, there were 6700 Σ^- and 1500 $\Sigma^+ \rightarrow \pi^+ + n$ events analyzed on the scanning table. The efficiency here was $\approx 95\%$. Thus, taking account of the available phase space, the effective branching fraction denominator becomes

$$0.20\,(0.95 \times 6700 + 1400) = 1550, \text{ for } \Sigma^-,$$

and

$$2 \times 0.20\,(0.95 \times 1500 + 300) = 680, \text{ for } \Sigma^+.$$

The factor of 2 in the last equation is corrected for the $\Sigma^+ \rightarrow \pi^0 + p$ decays, which did not need examination.

Thus the upper limits for Σ-muonic decays are

$$\frac{R(\Sigma^- \rightarrow \mu^-)}{R(\text{all decay modes})} \lesssim 1/1550 \approx 0.064\ \%,$$

and

$$\frac{R(\Sigma^+ \rightarrow \mu^+)}{R(\text{all decay modes})} \lesssim 1/680 \approx 0.15\%.$$

These fractions have been entered on line 4 of Table I; on line 5 they have been combined with existing data from line 2. We see that the combined fractions are in agreement with the prediction of line 3, scaled from empirical *electronic* rates.

III. Λ MUONIC DECAY

Whereas μ's from Σ decay at rest have a median momentum $p_\mu \approx 110$ MeV/c (range $R \approx 80$ cm), μ^-'s from Λ decay have a median $p_\mu \approx 65$ MeV/c ($R \approx 17$ cm), so that about one-third of them come to rest, even in our 15-inch chamber. The lowest curve of the figure represents the fraction of $\Lambda\mu$ decays that should be detected on the basis of the μ stopping ($p_\mu \lesssim 60$ MeV/c) in the 15-inch bubble chamber (*). The curve is based on a Monte Carlo analysis for various Λ momenta in which the muon spectrum in the Λ rest frame corresponded to non-Lorentz-invariant 3-body phase space, and this is expected to be a good approximation to β-decay spectra.

At first thought it seems that one can get a much higher μ-detection efficiency by using *measured* Λ decays. It is true that a Λ leptonic decay has only a small chance of kinematically fitting the hypothesis of normal Λ decay, but in order to prove that the leptonic decay is muonic and not electronic, the μ must be densely ionizing ($p \lesssim 75$ MeV/c). The next higher curve of Fig. 1, based on the same Monte Carlo experiment, shows the probability of detecting $\Lambda\mu$ decays having muons of less than 75 MeV/c. Thus for Λ of 200 MeV/c, our detection efficiency is 40% of all measured events, plus 30% for events that were scanned only. Both methods of detecting $\Lambda\mu$ decays become less efficient at higher Λ momenta, as shown. It appears that a better estimate of the $\Lambda\mu$ branching ratio could be realized from an experiment carried out in a larger chamber with low-energy lambdas, using *scanning* techniques to select $\Lambda\mu$ candidates.

From the 1958 experiment we had 900 measured Λ, and from the 1961 experiment we have 3337 Λ that have not yet been measured. Among these 4200 Λ we found no slow muons except those from obvious $\pi-\mu$ decays.

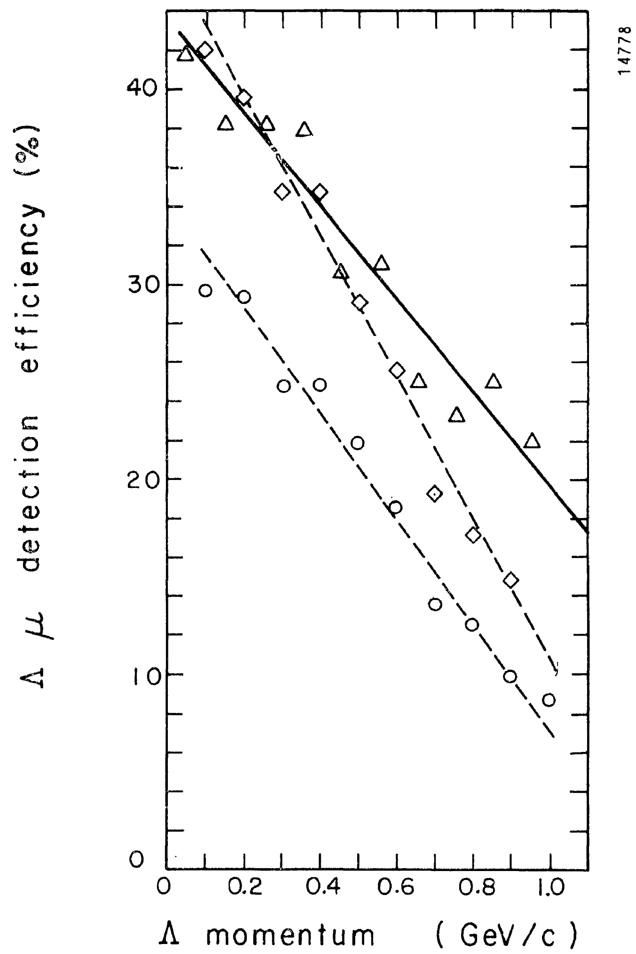

Fig. 1 The detection efficiency, based on Monte Carlo calculations, is shown for scanned events (circles) and measurement (squares) of Λ decays (fitted events) in the 15-inch hydrogen chamber, and for scanned events (triangles) in the 72-inch hydrogen chamber. The scanning efficiency is quite sensitive to the size of chamber used, as can be seen.

If we correct for the fact that one-third of the Λ's decay through the neutral channel, the effective denominator for the $\Lambda \to \mu$ branching ratio becomes

$$\frac{3}{2}[0.4(900)+0.3(3337)] = 2050 ,$$

and the branching ratio

$$\frac{R(\Lambda \to \mu)}{R(\text{all decay modes})} \lesssim \frac{1}{2000} \approx 0.05\%$$

Comparison of these experimental limits for hyperon muonic decays with the rates of row 1, Table I, suggests that the muonic decay rates are substantially lower than the Feynman and Gell-Mann predictions, following the established pattern of the electronic hyperon decays.

(*) If we had found a slow μ, we would still have had to show that it could not have come from a $\pi-\mu$ decay very close to the Λ. Therefore we have taken the detection efficiency to be 85% of the probability that a Λ decays with a μ momentum of less than 60 MeV/c.

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THE β DECAY OF THE Λ HYPERON

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We are studying the β decay of the Λ hyperons, $\Lambda \to p + e^- + \bar{\nu}$, from Λ's produced by stopping K^- mesons in the Berkeley 30″ propane chamber filled with a mixture of 55% C_3H_8 and 45% CF_3Br by volume. Approximately 275 000 pictures were taken in the separated 800 MeV/c K^- beam designed by J. Murray *et al.* [1]. The beam was degraded so that the K^- entered the chamber at 450 MeV/c and came to rest in the liquid.

To date, with about one-half of the film scanned we have observed 135.300 visible Λ's and 120 selected candidates of the lamba beta decay. The momenta of the Λ's range from 150 MeV/c to 500 MeV/c with a peak at 300 MeV/c. The detection efficiency for Λ's, determined by rescanning 1/5 of the film, was 85%. Correcting for the 1/3 which decay via the neutral mode, $\Lambda \to n + \pi^0$, the total number of Λ's produced in the region of film scanned is then 239 000.

The β decays were selected on the basis of one of the following criteria, (1) curvature incompatible with the π from a Λ decay, (2) δ-rays too large for a π, (3) the e^- stopped in the chamber, or (4) the negative track was too long for the π required from a Λ. These events were measured and discarded if the transverse momentum was too large for a β decay (163 MeV/c) or if the event was compatible with a normal Λ decay followed by a $\pi \to \mu \to e$ decay. We estimate that other interactions which may simulate Λ–β decay contribute less than 10% of the remaining sample.

In order to obtain the β decay rate we have used only those events in categories (2), (3) and (4) above. The detection efficiencies for category (3) were calculated as follows. The probability that an electron would stop in the chamber was determined from the Bethe-Heitler formula for radiation loss. A collision loss correction was made every 3 cm. (The radiation length of the collision mixture is near 22 cm and the critical energy is 40 MeV). The result was folded into the potential path length distribution observed from the path lengths of the negative prongs of the mesonic Λ decays and averaged over the momentum spectrum of the β decay which would be expected from a Lorentz invariant phase space. These formulas were checked by examining a sample of μ –e decays in