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MUONIC DECAYS OF $\Sigma$ AND $\Lambda$ HYPERONS

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May 31, 1962
MUONIC DECAYS OF \( \Sigma \) AND \( \Lambda \) HYPERONS*

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May 31, 1962
(To be presented by Arthur H. Rosenfeld)

I. INTRODUCTION

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

\[
\Sigma^\pm \rightarrow \mu^\pm + \nu + n
\]

and

\[
\Lambda \rightarrow \mu^- + \nu + p.
\]

Present values of the branching fractions are summarized in Table I. The theoretical fractions \( f_{\text{FGM}} \) 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 have proven to be lower than the \( f_{\text{FGM}} \) 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 \( \frac{\Sigma \rightarrow N + \mu + \nu}{\Sigma \rightarrow N + e + \nu} \) is proportional to their phase-space ratio. Muonic decay branching fractions, based on this phase space assumption, are listed in row 3 of the table.

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

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

II. $\Sigma$-MUONIC DECAY

The general technique used for $\mu$-decay detection was to scan for low-momentum decay products of $\Sigma$. The procedure has already been described in detail, but will be summarized briefly.

Normal $\Sigma^-$ decay ($\Sigma^-\rightarrow \pi^- + n$) produces pions with a pion momentum of about 192 MeV/c in the $\Sigma^-$ 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 $\Sigma^+$). 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 cutoff momentum $p_c = 80$ MeV/c.

The sources of background in order of decreasing importance are:

(1). Single and plural scattering of the $\pi^-$. In our earlier work on a sample of 750 selected $\Sigma^-$, 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 as to appear to have $p < p_c$. In this larger sample of 8000 selected $\Sigma^-$ we can reduce $\omega(p_c)$ to $< 0.006\%$ by choosing $p_c = 80$ MeV/c.

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

(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 \( \pi^\pm \rightarrow \mu^\pm + \nu \) decay within several millimeters and/or backwards in the \( \pi \) center of mass. The K-capture reaction \( K^- + p \rightarrow \Sigma^\pm + \pi^\pm \) yields a \( \Sigma \) with a momentum of about 180 MeV/c. Therefore, when the \( \Sigma \) 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 \( \mu \) 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 \( \Sigma \) muonic decay.

As a result of the above considerations we chose 80 MeV/c as the detection cutoff. 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 \( \Sigma \) momenta below 200 MeV/c.

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

There were 1400 \( \Sigma^- \rightarrow \pi^- + n \), and 300 \( \rightarrow \pi^+ + n \) 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 \( \Sigma^- \) 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

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

and

\[
2 \times 0.20 \times (0.95 \times 1500 + 300) = 680, \quad \text{for } \Sigma^+.
\]
The factor of 2 in the last equation corrected for the \( \Sigma^+ \rightarrow \pi^0 + p \) decays, which did not need examination.

Thus the upper limits for \( \Sigma \)-muonic decays are

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

and

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

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. \( \Lambda \) MUONIC DECAY

Whereas \( \mu \) from \( \Sigma \) decay at rest have a median momentum \( p \mu \approx 110 \) MeV/c (range \( R \approx 80 \) cm), \( \mu^- \) from \( \Lambda \) 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 \( \mu \) stopping \((p \mu \leq 60 \) MeV/c\) in the 15-inch bubble chamber. The curve is based on a Monte Carlo analysis for various \( \Lambda \) momenta in which the muon spectrum in the \( \Lambda \) rest frame corresponded to non-Lorentz-Invariant 3-body phase space, and this is expected to be a good approximation to \( \beta \)-decay spectra.

At first thought it seems that one can get a much higher \( \mu \)-detection efficiency by using measured \( \Lambda \) decays. It is true that a \( \Lambda \) leptonic decay has only a small chance of kinematically fitting the hypothesis of normal \( \Lambda \) decay, but in order to prove that the leptonic decay is muonic and not electronic, the
μ must be densely ionizing (p \leq 75 \text{ 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 \( \Lambda \) 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 \( \Lambda \) 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 \( \Lambda \), and from the 1961 experiment we have 3337 \( \Lambda \) that have not yet been measured. Among these 4200 \( \Lambda \) we found no slow muons except those from obvious \( \pi\mu \) decays.

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

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

and the branching ratio

\[
\frac{R(\Lambda \rightarrow \mu)}{R\ (\text{all decay modes})} \lesssim \frac{1}{2000} \approx 0.05\%.
\]

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.
ACKNOWLEDGMENT

We wish to thank Dr. Ronald R. Ross for his assistance.
REFERENCES AND FOOTNOTES


If we had found a slow $\mu$, we would still have had to show that it could not have come from a $\pi\mu$ decay very close to the $\Lambda$. Therefore we have taken the detection efficiency to be 85% of the probability that a $\Lambda$ decays with a $\mu$ momentum of less than 60 MeV/c.
Table I. Hyperon Muonic Decays.

<table>
<thead>
<tr>
<th>Branching Fractions, f(%)</th>
<th>$\Sigma^\mu^-$</th>
<th>$\Sigma^\mu^+$</th>
<th>$\Lambda\mu^-$</th>
<th>$\Sigma^e^-$</th>
<th>$\Sigma^e^+$</th>
<th>$\Lambda e^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Predicted by Feyman and Gell-Mann, $f_{\text{FGM}}$</td>
<td>2.5</td>
<td>1.01$^c$</td>
<td>0.3</td>
<td>5.6</td>
<td>2.3$^c$</td>
<td>1.6</td>
</tr>
<tr>
<td>2. Experimental, published to date, $f_{\text{exp}}$</td>
<td>&lt;0.2$^d$</td>
<td>0.3$^d,e$</td>
<td>0.1$^d,e$</td>
<td>see row (5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. $f(\mu)$ expected by scaling $f(e)$ data proportionally to phase space</td>
<td>0.05</td>
<td>0.04</td>
<td>0.04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. $f(\mu)$ reported in this note</td>
<td>0.065</td>
<td>0.15</td>
<td>0.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. All available data$^g$</td>
<td>&lt;0.05</td>
<td>0.1</td>
<td>0.03</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Detection Efficiency (%) | | | | | | |
|--------------------------| | | | | | |
| 6. By scanning only | 19 | $19\times2^i$ | $30\times2^i$ | 28 | 2X28 | --- |
| 7. On measured events | 20 | $20\times2^i$ | $40\times2^i$ | 33 | 2X33 | 70 |

---

$^a$ See reference 2.
$^b$ See references 1 and 7.
$^c$ From phase space. However, $\Sigma^\mu^+$ and $\Sigma^\mu^+$ decays were formerly believed to be forbidden by the $\Delta S = \Delta Q$ rule.
$^e$ Barbaro-Galtieri et al.
$^f$ 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 $\Sigma^-e^-$ and $\Lambda e^-$ events reported in (2), Bhowmik et al. report one $\Sigma^-e^-$ and two $\Lambda e^+$ events in a small sample of hyperon decays (Nuovo cimento 21, 567 and 1066 (1961)).
$^i$ The factor 2 is due to the $\Sigma^-\mu^-p+\pi^0$ decay mode which will not be confused with $\Sigma^\mu^-n+\mu^+ + \nu$.
$^j$ The factor $3/2$ corrects for the neutral decay mode of the normal $\Lambda$ decay.
FIGURE LEGEND

Fig. 1. The detection efficiency, based on Monte Carlo calculations, is shown for scanned events (circles) and measurement (squares) of $\Lambda$ 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.
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