DETERMINATION OF THE BETA DECAY RATE OF THE SIGMA HYPERON AND THE $\Delta S = \Delta Q$ RULE*

E. Bierman, S. Kounosu,† U. Nauenberg, and L. Seidlitz‡
Palmer Physical Laboratories, Princeton University, Princeton, New Jersey

and

A. P. Colleraine
Department of Physics and Astronomy, University of Maryland, College Park, Maryland
(Received 2 May 1968)

We have found the branching ratio for the electronic decay of the Σ^- to be $R(\Sigma^- \to n + e^- + \bar{\nu})/R(\Sigma^- \to n + \pi^-) = (1.11 \pm 0.09) \times 10^{-3}$. Similarly, in a measurement of 5×10^4 $\Sigma^+ \to n + \pi^+$ decays we have found no example of decays of the type $\Sigma^+ \to n + e^+ + \nu$ or $\Sigma^+ \to n + \mu^+ + \nu$. This gives an upper limit of 6.3% (90% confidence level) on the relative rate $R(\Delta S = -\Delta Q)/R(\Delta S = +\Delta Q)$ for the process in this experiment.

We describe here the results of an experiment that has determined the Σ^- electronic decay rate; the result obtained is consistent with previous values within the errors quoted.[1,2] We have also obtained an upper limit on the violation of the $\Delta S = \Delta Q$ rule in the Σ leptonic decays by a search for the decay $\Sigma^+ \to n + e^+ + \nu$ and find that this limit is in agreement with that of Baggett et al.[3] A comprehensive discussion of this experiment will be published elsewhere.

Sigma hyperons were produced by a stopping K^- beam in the Brookhaven National Laboratory 30-in. hydrogen bubble chamber, and we have measured a sample of 259 400 $\Sigma^- \to n + \pi^-$ and 62 100 $\Sigma^+ \to n + \pi^+$ decays. From these data we have identified 195 decays of the type $\Sigma^- \to n + e^- + \bar{\nu}$ and 12 decays of the type $\Sigma^- \to n + \mu^- + \bar{\nu}$, where the μ^- stops in the chamber and could not come from a π^- decay. We have not observed any Σ^+ decay which is compatible only with the modes $\Sigma^+ \to n + e^+ + \nu$ or $\Sigma^+ \to n + \mu^+ + \nu$, although we have one positron candidate which has a momentum below 70 MeV/c in the Σ^+ rest frame and which could be an example of the allowed decay $\Sigma^+ \to \Lambda^0 + e^+ + \nu$.

The data-reduction technique used was the same as that in a previous experiment,[2] with the exception that we have now restricted our attention to c.m. momenta ≤ 160 MeV/c for the charged decay track from the Σ. This has reduced the number of events in which the mass of the decay particle has to be determined by ionization measurements. With this cutoff on momentum we detect 81.8% of the spectrum for the electronic decay mode.[4]

To enable accurate ionization measurements to be made on dipping tracks, the length of the decay track was required to be at least 10 cm for dips up to 50° in the lab and at least 15 cm for dips between 50° and 60°. Events with dip greater than 60° were rejected. We also required the length of the Σ^- to be ≤ 0.95 cm so that the momentum of the Σ^- at its decay point is always ≥ 80 MeV/c. This eliminates a variety of reactions that can arise from $\Sigma^- p$ capture and can give rise to a 2-3% background. No minimum $\Sigma^\pm$-length criterion was imposed other than that the measurer should be able to see the Σ and its collinear production pion. Only 194 300 $\Sigma^- \to n + \pi^-$ decays and 49 100 $\Sigma^+ \to n + \pi^+$ decays remained after these cuts were made. The sigma-length cutoff reduced the sample of $\Sigma^- \to n + e^- + \bar{\nu}$ decays to 180. In addition we also make a subtraction of 0.7% from the total number of Σ^- decay to take into account events which were really Λ^0, Dalitz-pair productions, etc., at the end of a stopping K^- which would have the same topology as Σ-production reactions.

Those events in which the decay track from the Σ had a momentum ≤ 160 MeV/c in the Σ rest frame were considered to be candidates for the leptonic decay modes and were checked on a scanning table. The events which did not have obvious large kinks, characteristic of the $\pi \to \mu$ decays in flight or πp scatterings, were remeasured on more accurate Vanguard machines. Events which still had low decay-track momenta were examined by a physicist, and tracks that were not obvious electrons, stopping pions, or muons were gap counted. In Fig. 1 we show the relative ionization measured for each such track. This was determined by measuring the mean gap length of the track and comparing it with the mean gap length of a nearby minimum-ionizing ($P \sim 450$ MeV/c) beam-pion track or with the production-pion track from the same event after appropriate corrections for the dip of the decay and the comparison track had been made. For

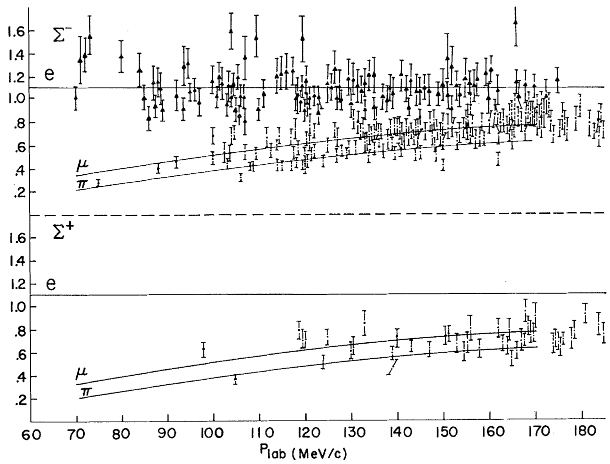

FIG. 1. Gap-density distribution for the Σ^- and Σ^+ decays. The lines labeled e, μ, π, are the predictions based on the $1/\beta^2$ law, where β is the velocity of the particle.

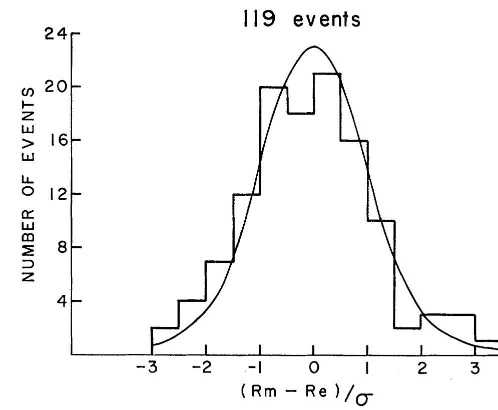

FIG. 2. Distribution of the gap-density measurement for those events considered as electrons. In the region $P_{\text{lab}} > 155$ MeV/c we define an electron as being a decay track whose gap distribution gives a value in Fig. 1 which is >1.0. There are eight events with gap counts between 0.9 and 1.0. These we consider ambiguous. We have taken four of those and considered them as electrons. These four are included in this figure.

low-momentum or steeply dipping decay tracks, the gap counting was done by microscope. For other decay tracks ($P \gtrsim 120$ MeV/c in the lab, nondipping), a Vanguard measuring machine was modified to record the passage of successive track bubbles across the reticle. At each bubble the X-Y digitizers of the precision stage were interrogated and a histogram of the gap-length distribution so obtained was stored. As can be seen from Fig. 1(a) the separation between electrons and muons or pions is clear. There are only eight events, shown with broken error bars and occurring at $P_{\text{lab}} \gtrsim 155$ MeV/c, for which the ionization measurement does not lead to a definite conclusion on the identity of the decay track. In computing the branching ratio for the electronic decay rate we have assumed one-half of these events to be electrons; the error introduced by this procedure is small compared with the statistical error. As an additional check on the gap-counting procedure, we plot in Fig. 2 the difference between the measured and expected ionization divided by the statistical error for those tracks identified as electrons. This distribution is fitted well by a Gaussian of unit width indicating a reasonable assignment of the error and the minimum detectable gap length. Also notice that any background from pions or muons would lead to an excess of events in the tail on the left-hand side of the peak. In Fig. 1(b) we show the ionization measurements of those Σ^+ decays in which the decay track could not positively be identified by eye as not being a positron. There is no candidate for the decay $\Sigma^+ \rightarrow n + e^+ + \nu$ in the present experiment.

During the course of the measurements weekly checks were made to ensure the uniformity of the measuring and computation processes. The measurers were required to make a photographic print of each obvious electronic decay or stopping π or μ which they saw. These events were subsequently compared with the output from our computer programs to verify that the programs made the correct interpretation in each case. One source of bias was detected in this way; we found that very low-momentum spiraling electrons would be rejected because either less than 10 cm of track would be measured or the rate of change of curvature was large enough to cause problems in the spatial reconstruction program. There were 5 such events in the data and they have been included after a more careful remeasurement. There were also 6 stopping μ^- tracks which were less than 10 cm long; these have also been included in our results. Other sources of bias such as loss of events in the analysis, poor measurements, etc., were checked and these lead to an error that is less than 2 %. This error affects the numerator and denominator of our branching ratio in approximately the same way; nevertheless it has been combined with the statistical error. We have also checked the distributions of the decay track dip, Σ decay lengths, and angles for both the leptonic and nonleptonic modes, and have found that the distributions coincide very closely.

The momentum spectrum of electrons from the decay $\Sigma^- \to n + e^- + \bar{\nu}$ is shown in Fig. 3. The curve shown, representative of a matrix element given by $F_1 = -0.211$, $G_1 = 0.103$, $F_2 = 0.0$,[5] fits the data very well ($\chi^2 = 5$ for 15 degrees of freedom). Four events on this plot for $P_{\text{c.m.}} \leq 70$ MeV/c have to be subtracted as being from the allowed background process $\Sigma^- \to \Lambda^0 + e^- + \bar{\nu}$, where the Λ^0 is not observed. From the known rate[6] for this decay mode we expect 12 ± 2 events of this type in our data; we have found eight events with a visible Λ^0 so that we subtract 4 ± 2. Hence the branching ratio or Σ^- electronic decays to $\Sigma^- \to n + \pi^-$ decays is

$$\frac{R(\Sigma^- \to n + e^- + \bar{\nu})}{R(\Sigma^- \to n + \pi^-)} = \frac{(180 \pm 13) - (4 \pm 2)}{1.943 \times 10^5 \times 0.818 \times 0.993} = (1.11 \pm 0.09) \times 10^{-3}.$$

The denominator has been corrected for the 81.8% of the electron spectrum detected and for the 0.7% correction to the number of fake $\Sigma^- \to n + \pi^-$ decays mentioned before.

From the measurements on the $\Sigma^+ \to n + \pi^+$ decays we can set a limit on the violation of the $\Delta S = +\Delta Q$ rule which could occur in Σ leptonic decays. We have observed one event with a low-momentum positron which is probably an example of the allowed decay $\Sigma^+ \to \Lambda^0 + e^+ + \nu$. In addition we have seen two Σ^+ decays in which the decay track was a stopping μ^+. However, the momentum of the muons was high enough so that they could be from $\pi^+ \to \mu^+$ decays in flight, where the π^+ decays within the first 3 mm. To obtain a limit on the $\Delta S = +\Delta Q$ rule we confine our attention only to the electronic decay modes and compare the number of e^+ and e^- candidates which have c.m. lepton momenta in the range $70 < P_{\text{c.m.}} \leq 160$ MeV/c to exclude the allowed background process mentioned above. With this constraint the useful fraction of phase space detected is now 66%; hence the limit on the relative rates of $\Delta S = -\Delta Q$ to $\Delta S = +\Delta Q$ processes is

$$\frac{R(\Delta S = -\Delta Q)}{R(\Delta S = +\Delta Q)} = \frac{2.3}{49\,100 \times 0.66} \times \frac{1}{1.11 \times 10^{-3}} = 6.3\%,$$

where the factor 2.3 represents the 90% confidence level for this rate violation.

To date only one example of the decay $\Sigma^+ \to n + e^+ + \nu$ has been observed.[2] We would like to suggest that this event could be an example of the de-

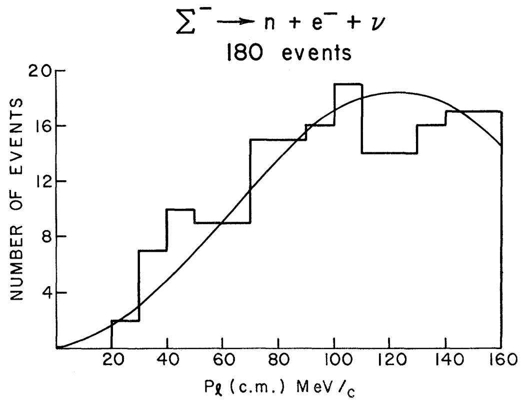

FIG. 3. Momentum distribution of electrons in the sigma rest frame. The curve drawn is representative of a matrix element given by $F_1 = -0.211$, $G_1 = 0.103$, $F_2 = 0.0$. A curve with the same F_1 and G_1 but $F_2 = 0.274$ would also be a good fit to the data.

cay chain

$$\Sigma^+ \to p + \pi^0, \quad \pi^0 \to e^+ + e^- + \gamma,$$

where the proton and the e^- are not visible. The probability of not seeing the proton is 8%, the Dalitz decay mode of the π^0 occurs 1/80 of the time, and probability of not seeing the electron is ~0.2%; thus we would expect to see two such events in every 10^6 $\Sigma^+ \to n + \pi^+$ decay. The effective sample of Σ^+ decays measured by various groups[1-3] is at present about 1.25×10^5 so that the probability of this interpretation being correct is 20%. In addition, two possible events of the type $\Sigma^+ \to n + \mu^+ + \nu$ have been found.[7,8] If we include all data published so far, the one positron event represents an upper limit on the $\Delta S = -\Delta Q$ rate of 4.1% (90% confidence level) or a limit of 0.20 on the amplitude. If, on the other hand, the positron candidate is a background event, the limit on the rate would be 2.4% (0.16 on the amplitude). Recent experiments[9] indicate that the violation of the $\Delta S = +\Delta Q$ rule in $K_{e3}{}^0$ decay is 0.28 ± 0.09 in amplitude. If it should turn out to be the case that a real difference exists between the hyperon and kaon amplitudes, one would have to resort to a model which makes the $K_{e3}{}^0$ channel more sensitive to this rule.[10]

Finally, we have used this new value of the Σ^- electronic decay rate averaged with that quoted by Rosenfeld et al.[11] [giving a branching ratio of $(1.14 \pm 0.09) \times 10^{-3}$] and the latest values for other baryon leptonic decay rates to determine the values of the parameters F, D, and θ in the Cabibbo theory.[12] The procedure adopted was to find a minimum-χ^2 solution to the set of equations of Willis et al.,[13] with the exception that we have not incorporated the meson-decay data. We have, however, favored a lower rate for the process $\Lambda^0 \to p + e^- + \bar{\nu}$ than is reported as the average in the current Berkeley tables.[11] We find the values $F = -0.442 \pm 0.033$, $D = -0.759 \pm 0.034$, and $\theta = 0.241 \pm 0.011$. These are consistent with the comprehensive work of Carlson[14] within the errors quoted.

We would like to thank Dr. David Berley for his excellent beam design, Dr. Al Prodell and the 30-in. bubble chamber crew for their help during the exposure, and the Princeton scanning group for a superb job in this experiment.

---

*Work supported by the U. S. Atomic Energy Comission.

†Present address: University of Lethbridge, Lethbridge, Alberta, Canada.

‡Present address: Berkeley Scientific Laboratories, 2229 4th Street, Berkeley, Calif.

[1]H. Courant et al., Phys. Rev. 136, B1791 (1964); D. J. Miller et al., Phys. Letters 11, 262 (1964); C. T. Murphy, Phys. Rev. 134, B188 (1964).

[2]U. Nauenberg, P. Schmidt, J. Steinberger, S. Marateck, R. J. Plano, H. Blumenfeld, and L. Seidlitz, Phys. Rev. Letters 12, 679 (1964).

[3]N. Baggett, T. B. Day, R. G. Glasser, B. Kehoe, R. Knop, B. Sechi-Zorn, and G. A. Snow, Phys. Rev. Letters 19, 1458 (1967).

[4]This number is based on the form of the matrix element given in M. M. Nieto, Rev. Mod. Phys. 40, 140 (1968), without any weak-magnetism (F_2) term. If weak magnetism is included ($F_2 = 0.274$) the fraction of the electron spectrum detected is 0.777 and the branching ratio we quote would have to be multiplied by 1.05.

[5]Nieto, Ref. 4.

[6]N. Barash, T. B. Day, R. G. Glasser, B. Kehoe, R. Knop, B. Sechi-Zorn, and G. A. Snow, Phys. Rev. Letters 19, 18 (1967).

[7]A. Barbaro-Galtieri et al., Phys. Rev. Letters 9, 26 (1962).

[8]F. Eisele et al., Z. Physik 205, 405 (1967).

[9]Mark Sakitt, private communication. The previously published value (based on a smaller sample of events) was $|\chi| = 0.26^{+0.08}_{-0.11}$, indicating that the error is not Gaussian. See D. G. Hill et al., Phys. Rev. Letters 19, 668 (1967). This article contains references to all earlier work in this subject.

[10]See, for example, Eduardo de Rafael and Maurice Goldhaber, Phys. Rev. Letters 20, 522 (1968).

[11]A. H. Rosenfeld et al., University of California Radiation Laboratory Report No. UCRL 8030, January, 1968 (unpublished), and Rev. Mod. Phys. 40, 77 (1968). The experiments of Robert P. Ely et al., Phys. Rev. 131, 868 (1963), and C. Baglin et al., Nuovo Cimento 35, 977 (1965), combined with the preliminary results of the Maryland group [B. Sechi-Zorn, private communication; J. Maloney and B. Sechi-Zorn, Bull. Am. Phys. Soc. 13, 16 (1968)] give an average value of $(0.79 \pm 0.10) \times 10^{-3}$ which has been used in this fit.

[12]N. Cabibbo, Phys. Rev. Letters 10, 531 (1964).

[13]W. Willis et al., Phys. Rev. Letters 13, 291 (1964); see also Courant, Ref. 1.

[14]C. Carlson, Phys. Rev. 152, 1433 (1966); see also N. Brene et al., Phys. Rev. 149, 1288 (1966), and N. Brene et al., CERN Report No. 68/181/5, 1968 (unpublished).

PREDICTION OF THE ISOVECTOR NUCLEON FORM FACTOR $F_1^V(t)$ †

J. G. Cordes and P. J. O'Donnell
Department of Physics, University of Toronto, Toronto, Canada
(Received 1 March 1968; revised manuscript received 15 April 1968)

One of the major theoretical problems in electromagnetic interactions in recent years has been the explanation of the so-called dipole fit for the nucleon form factors. Recent experiments at Stanford Linear Accelerator Center[1] have confirmed that the form factor $G_M^p(t)/\mu_p$ behaves according to the empirical relation

$$G_M^p(t)/\mu_p = (1 - t/0.71)^{-2} \tag{1}$$

for $|t| < 25$ $(\mathrm{GeV}/c)^2$.

It has also been observed from the data that the following symmetry relations hold[2]:

$$G_E^p(t) = G_M^p(t)/\mu_p = G_M^n(t)/\mu_n, \tag{2}$$

and[3]

$$G_E^n(t) \approx 0. \tag{3}$$

These results are difficult to understand on the basis of the usual pole dominance by vector particles of the dispersion relations for $G_E(t)$ and $G_M(t)$. It is clear, for example, that the ρ meson is not sufficient to explain the t^{-2} behavior of $G_E^V(t)$, since in dispersion theory a single resonance leads to a t^{-1} behavior far from the resonance. It seems natural, therefore, to try to fit the data by including a second isovector resonance since then the t^{-2} behavior can be obtained. Such a two-pole fit for $G_E^V(t)$ does not account for the data unless the mass of the new