217 (1967).

[6]H. C. Goldwire, Jr., and F. C. Michel, Astrophys. J. Letters 156, L111 (1969).

[7]It has been brought to my attention that similar conclusions have been reached by P. Goldreich (Ref. 14 quoted in Ref. 2 above), but I have not yet seen a copy of this reference. See also A. J. Deutsch, Ann. Astrophys. 18, 1 (1955).

EXPERIMENTAL TEST OF UNIVERSALITY IN $\Sigma^- \to nl^-\nu$*

N. V. Baggett,†‡ B. Kehoe, and G. A. Snow
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742
(Received 6 June 1969)

In a 540 000-frame stopping-K^- exposure at the Brookhaven National Laboratory alternating-gradient synchrotron, the branching ratio $\Gamma(\Sigma^- \to n\mu^-\nu)/\Gamma(\Sigma^- \to \text{all})$ is found to be $(0.43 \pm 0.09)\times 10^{-3}$. Combining this with the world-average $\Sigma^- \to ne^-\nu$ branching ratio of $(1.10 \pm 0.05)\times 10^{-3}$ gives $\Gamma_\mu/\Gamma_e = 0.39 \pm 0.08$, which agrees with the universal $V-A$ prediction of 0.45.

One of the most straightforward tests of μ-e universality and the V–A interaction[1] in strange-particle leptonic decays is a measurement of the ratio of the Σ^- decay rates: $\Gamma(\Sigma^- \to n\mu^-\nu)/\Gamma(\Sigma^- \to ne^-\nu)$. If we assume μ-e universality, but not the V–A form, the matrix element for $\Sigma \to nl\nu$ can be written

$$M \propto \sum_{i=1}^{5} C_1(\bar{u}_n\Gamma_i u_\Sigma)[\bar{u}_l\Gamma_i(1+\gamma_5)u_\nu],$$

where $l = \mu$ or e; the Γ_i are the five Lorentz covariant operators 1 (S), γ_5 (P), γ_α (V), $\gamma_\alpha\gamma_5$ (A), and $\sigma_{\alpha\beta}$ (T); and the C_i are the coupling constants. In this general case, the μ-e ratio is given by[2]

$$R = \frac{\Gamma(\Sigma^- \to n\mu^-\nu)}{\Gamma(\Sigma^- \to ne^-\nu)} = 0.45 + 0.60\gamma, \quad (1)$$

with

$$\gamma = \frac{\mathrm{Re}C_S C_V^* - 6\,\mathrm{Re}C_A C_T^* + 6\delta\,\mathrm{Re}C_V C_T^* - \delta\,\mathrm{Re}C_P C_A^*}{|C_S|^2 + |C_V|^2 + 3|C_A|^2 + 12|C_T|^2},$$

and

$$\delta = \frac{M_\Sigma - M_n}{M_\Sigma + M_n}.$$

Equation (1) is valid up to $O(\delta^2)$.

The quanity γ clearly vanishes if the interaction is pure V and A. It could also vanish due to an accidental cancellation, which is unlikely a priori. If we assume V–A, then the ratio R provides a test of μ-e universality.

We have scanned 540 348 frames of stopping-K^- film, obtained at the Brookhaven alternating-gradient synchrotron 30-in. hydrogen bubble chamber, for the decays $\Sigma^- \to n\mu^-\nu$.[3] The events were identified by seeing the μ^- stop in the chamber and decay to an electron. All events were required to satisfy the following criteria: (1) Σ^- produced by at-rest K^-, (2) $0.1 \leq \Sigma^-$ length ≤ 0.95 cm, (3) $|\mu \text{ dip}| \leq 60°$, and (4) $32 \leq \mu$ momentum ≤ 80 MeV/c.

The upper length cut on the Σ^- removes background due to Λ's produced by stopping Σ^-'s. The upper μ momentum cut removes background due to $\Sigma \to n\pi$, $\pi \to \mu\nu$, where the π-μ decay is undetected. There is a small background due to the radiative decays $\Sigma \to n\pi\gamma$, $\pi \to \mu\nu$. A Monte Carlo calculation shows that this background is <1 event. Since we expect <1 genuine $\Sigma^- \to \mu^-$ event to be rejected because of a sizable plural scattering kink, we make no subtraction for radiative background.

A total of 56 events were found which satisfy all of our criteria. In order to determine the scanning efficiency, a special second scan was undertaken, in which only $\Sigma \to \mu$ and $\Sigma \to \pi \to \mu$ events were recorded. About half the film was scanned in this way. The first scan was found to have a momentum-dependent efficiency. In order to take this into account with minimum increase in statistical error, the events were divided into momentum regions: (I) $32 \leq p_\mu \leq 55$ MeV/c and (II) $55 < p_\mu \leq 80$ MeV/c. The scanning efficiencies, based on 26 events found in the double-scanned film, were the following:

	Region I	Region II
First scan	(80 ± 13) %	(43 ± 12) %
Second scan	(89 ± 10) %	(86 ± 13) %

The 56 events were divided into groups according to their momentum and to the scan or combination of scans in which they were found. Each event was weighted by the inverse of the efficiency for its group. Each event was also weighted by the inverse of the probability that a μ of that

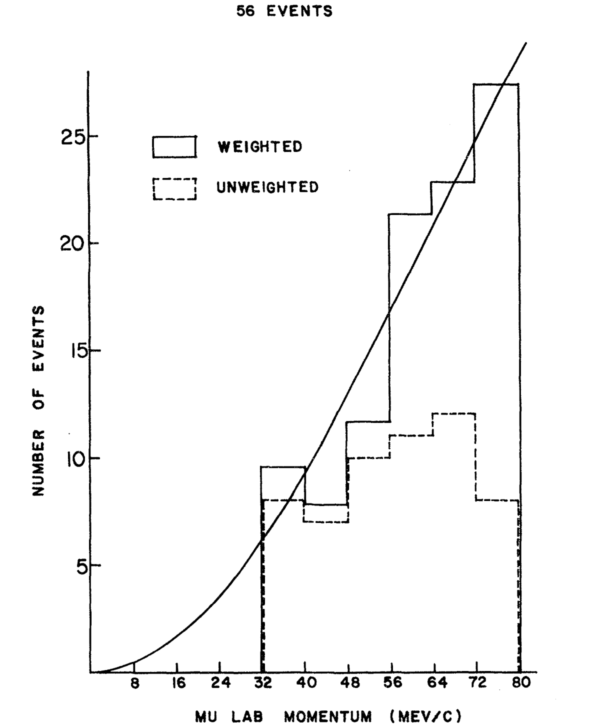

FIG. 1. Observed $\Sigma^- \to n\mu^-\nu$ events weighted for scanning efficiency and stopping probability.

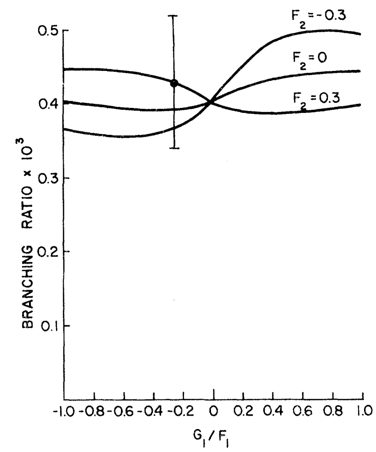

FIG. 2. Effect of coupling constants on branching ratio $\Gamma(\Sigma^- \to n\mu^-\nu)/\Gamma(\text{all } \Sigma^-)$.

momentum will stop within the chamber. The stopping probability function was obtained by a Monte Carlo calculation.[3] Figure 1 shows a histogram of the events, weighted and unweighted, compared with the theoretical spectrum.

In order to determine the total μ^- branching ratio the theoretical fraction of the μ^- spectrum between 32 and 80 MeV/c is needed. This quantity is somewhat sensitive to the weak magnetism term in the interaction. Using the values[4] $F_1 = -0.233$, $F_2 = 0.303$, and $G_1 = 0.058$ for the vector, weak-magnetism, and axial-vector coupling constants, respectively, we find the fraction between 32 and 80 MeV/c to be 19.4%. The total number of Σ^- produced by at-rest K's in the film was determined by a separate scan to be $(2.08 \pm 0.05) \times 10^6\ \Sigma^-$.[3] Combining the above experimental results, we obtain for the total μ^- branching ratio

$$\frac{\Gamma(\Sigma^- \to n\mu^-\gamma)}{\Gamma(\text{all } \Sigma^-)} = (0.43 \pm 0.09) \times 10^{-3}.$$

Figure 2 shows the effect on this branching ratio of varying G_1/F_1 and F_2 over a reasonable range. These variations change the calculated fraction of the μ^- spectrum between 32 and 80 MeV/c. It can be seen that the present experimental error in the μ^- branching ratio is larger than this theoretical uncertainty.

To determine the μ-e ratio, we use the world-average $\Sigma^- \to ne^-\nu$ branching ratio[5]

$$\frac{\Gamma(\Sigma^- \to ne^-\nu)}{\Gamma(\Sigma^- \to \text{all})} = (1.10 \pm 0.05) \times 10^{-3}.$$

Table I gives the branching ratio, the μ-e ratio, and the parameter γ defined above. For comparison, the results from the $\Sigma^- \to n\mu^-\nu$ branching ratio of the Heidelberg group[6] are also shown. The two experiments are in good agreement, and both are consistent with μ-e universality and the V-A interaction.

Alternative tests of μ-e universality in strange-particle decays are provided by comparison of μ and e decays in K_{l2} and K_{l3} decays.[7,8] Both agree

Table I. Test of μ-e universality and V-A interaction.

	$\frac{\Gamma(\Sigma^- \to n\mu^-\nu)}{\Gamma(\Sigma^- \to \text{all})} \times 10^3$	$\frac{\Gamma(\Sigma^- \to n\mu^-\nu)}{\Gamma(\Sigma^- \to ne^-\nu)}$	γ
This experiment	0.43 ± 0.09	0.39 ± 0.08	$-0.23 < \gamma < 0.03$
Heidelberg[a]	0.45 ± 0.08	0.41 ± 0.08	$-0.20 < \gamma < 0.07$
Average	0.44 ± 0.06	0.40 ± 0.06	$-0.18 < \gamma < 0.02$
Theory	0.48[b]	0.45	0

[a]Ref. 6.

[b]One-angle Cabibbo fit taken from Filthuth (see Ref. 4).

with μ-e universality, the former to an accuracy of ~20% and the latter to an accuracy of ~14% when the present uncertainty in the ratio f_-/f_+ is taken into account.

We would like to thank Dr. D. Berley, Dr. A. Prodell, and the crews of the Brookhaven National Laboratory 30-in. hydrogen bubble chamber and alternating-gradient synchrotron for their generous assistance, and our scanning staff for their persistent and loyal scanning efforts.

*Work supported in part by the U. S. Atomic Energy Commission.

†Work is based on a dissertation in partial fulfillment of the requirements for a Ph. D. degree at the University of Maryland.

‡Present address: Institute for High Energy Physics, Heidelberg University, Heidelberg, Germany.

[1]E. C. G. Sudarshan and R. E. Marshak, in Proceedings of the Padua-Venice Conference on Mesons and Recently Discovered Particles, September, 1957 (Società Italiana di Fisica, Padua-Venice, 1958), reprinted in P. K. Kabir, Development of Weak Interaction Theory (Gordon and Breach, Publishers, Inc., New York, 1963), pp. 118-128; R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958).

[2]H. Pietschmann and E. Streeruwitz, "On the μ-e Ratio for Semi-Leptonic Hyperon Decays" (to be published).

[3]N. V. Baggett, University of Maryland Technical Report No. 973, 1969 (unpublished).

[4]The coupling constants are defined according to M. M. Nieto, Rev. Mod. Phys. 40, 140 (1968). The values used here are derived from the most recent values of the Cabibbo parameters: $F=-0.49\pm0.02$, $D=-0.74\pm0.02$, and $\theta=0.235\pm0.006$, given by H. Filthuth, review talk at the Topical Conference on Weak Interactions, CERN, Geneva, Switzerland, January, 1969 (unpublished) [CERN Report No. CERN 69-7 (unpublished)].

[5]Filthuth, Ref. 4. This average includes data from the Columbia–Stony Brook Collaboration, and the Maryland, Heidelberg, and Princeton groups, contributed to the Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September, 1968 (unpublished)).

[6]G. Ang, F. Eisele, R. Engelmann, H. Filthuth, W. Föhlisch, V. Hepp, E. Leitner, P. Mokry, W. Presser, H. Schneider, M. L. Stevenson, H. Ströbele, and G. Zech, in Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September, 1968 (unpublished), Contribution No. 572.

[7]R. Macek, A. K. Mann, W. K. McFarlane, J. B. Roberts, K. W. Rothe, C. H. West, and L. B. Auerbach, Phys. Rev. Letters 22, 32 (1969); D. R. Botterill, R. M. Brown, I. F. Corbett, G. Culligan, J. McL. Emmerson, R. C. Field, J. Garvey, P. B. Joens, N. Middlemas, D. Newton, T. W. Quirk, G. L. Salmon, P. Steinberg, and W. S. C. Williams, Phys. Rev. 171, 1402 (1968), and Phys. Rev. Letters 19, 982 (1967).

[8]J. W. Cronin, in Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September, 1968 (CERN Scientific Information Service, Geneva, Switzerland, 1968), p. 284.

WHAT NEXT WITH SOLAR NEUTRINOS?*

John N. Bahcall†
California Institute of Technology, Pasadena, California 91109
(Received 27 June 1969)

The capture rate of solar neutrinos is estimated for a number of targets that have been suggested previously as possible detectors of solar neutrinos. It is shown that the most important feasible experiment to be carried out in the future employs ^{7}Li as a detector.

The purpose of this Letter is to suggest that according to certain criteria the most important, feasible experiment involving solar neutrinos, following the ^{37}Cl experiment of Davis, Harmer, and Hoffman,[1] is one in which ^{7}Li is used as a detector. We first summarize the present theoretical and experimental situations regarding solar neutrinos and then present a table of the estimated capture rate of neutrinos for a number of possible targets. Using this table we show why, among the many experiments that have been proposed previously,[2-8] an experiment using ^{7}Li now seems most desirable.

Recent theoretical work has established the dependence of the estimated capture rate in the ^{37}Cl experiment on the parameters assumed and the assumptions made concerning the way nuclear fusion reactions generate the solar luminosity.[9] It is convenient in discussing solar neutrino experiments to introduce a solar neutrino unit: 1 SNU $=10^{-36}$ capture per target particle per second.[10] If the CNO cycle is the dominant energy sourcs in the sun the expected capture rate is 35 SNU,[11] the rate estimated from the p-p chain using "standard values" for all nuclear and composition parameters is 6 SNU,[10, 12] the rate determined by using[13] ^{7}Li$(n,n')^7$Li$(n,\gamma)^8$Li to estimate the low-energy cross-section factor (S_{17}) for the