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[1]In this paper, we have ignored possible A_2 splitting. Recent experiments [see, e.g., P. Weilhammer *et al.*, Bull. Am. Phys. Soc. 16, 610 (1971); S. J. Lindenbaum *et al.*, *ibid.* 16, 610 (1971); and B. Gottschalk *et al.*, *ibid.* 16, 610 (1971)] have presented evidence against splitting, leading to more controversy on this point. We point out that, if the A_2 is split, this analysis must be modified to include the correct phase dependence of the A_2, or, with sufficient statistics, could be modified to *determine* this phase dependence.

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Measurement of the Ratio of the Axial-Vector to the Vector Coupling in the Decay $\Sigma^- \to ne^-\bar{\nu}$†

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From a sample of 393 Σ^- β decays, we have selected 63 events in which a proton recoil from a neutron interaction in the chamber is observed. From the measured values of the electron-neutrino angle we conclude that for the $\Sigma^- \to ne^-\bar{\nu}$, $|g_A/g_V| = 0.29^{+0.28}_{-0.29}$. This result is obtained from a maximum-likelihood calculation which includes the effect of a well-understood background of 27± 6 events contained in our sample.

I. INTRODUCTION

The ability of the Cabibbo[1] theory to correlate all data on leptonic decays of hadrons has prompted a series of experiments to improve the experimental information on such decays. In particular, on the basis of the rates alone for leptonic decays, the theory can predict the magnitude of the vector and axial-vector coupling, thus inviting more direct comparisons with observations.

Methods by which the relative amounts of such couplings can be determined in the leptonic decay of a spin-$\frac{1}{2}$ baryon into three fermions are well known.[2,3] For the decay of unpolarized baryons and when the polarization of the decay baryon is not observed, the electron-neutrino correlation or equivalently the baryon recoil spectrum is very sensitive to the type of interaction, but not the relative sign of the two couplings. In the case of the decay $\Sigma^- \to n + e^- + \bar{\nu}$, the presence of two neutral particles in the final state makes the determination of the relevant correlation very difficult. However, since it is easier to produce a large number of unpolarized Σ^- hyperons than polarized ones, we preferred to confront the problem of neutron detection. Since the rate for this decay has been measured separately,[4] we report in this paper only the determination of the absolute ratio of the coupling constants $|g_A/g_V|$. Experiments with the same goal, where, however, the correlation between electron and Σ^- polarization is measured, have also been performed.[5,6] Preliminary results of this experiment have been reported elsewhere.[7,8]

II. EXPERIMENTAL METHOD

A copious source of Σ^- hyperons is the capture reaction at rest, $K^- + p \to \Sigma^- + \pi^+$. We have used a 550 000-frames exposure of the Columbia-BNL hydrogen bubble chamber exposed to the low-energy separated K^- beam at the Brookhaven Alternating Gradient Synchroton (AGS). Approximately five million K^- mesons stopped in the chamber, producing some two million Σ^- hyperons. The branching ratio for β decay of Σ^- is of the order of 10^{-3}, thus some 2000 such decays are in the exposure together with approximately 2×10^6 $\Sigma^- \to n\pi^-$ and $\Sigma^- \to n\pi^-\gamma$ decays. This 1000 to 1 background constitutes the first of the rather severe experimental problems. The second experimental problem is presented by the neutron detection and by the measurement of its momentum. Less than 10% of the neutrons scatter in the chamber liquid producing an observable proton recoil. Measurement of such tracks and energy and momentum conservation at the neutron-proton interaction determine the neutron angle and momentum. Consequently the leptonic Σ^- decay is in principle overdetermined, thus allowing the selection of a pure sample of such decays.

III. IDENTIFYING Σ^- β DECAYS

The first part of our experiment consisted of separating as many β decays as possible from a huge sample of all Σ^- decays. This separation was performed in several ways.

A. Scan

A multiple scan found all obvious examples of Σ^- β decay with no ambiguity in the identification of the events. This method is highly efficient for electron momentum below 80 MeV/c in the laboratory, approximately one-quarter of the total electron spectrum. A separate scan with less stringent requirements was performed on 60% of the film and identified additional Σ^- β decays.

B. Measurement

Our second procedure was to kinematically identify and subsequently discard pionic decays. We measure all Σ^- decays and, after geometric reconstruction, check for consistency with two-body decay by transforming the negative particle, assuming it is a pion, to the rest frame. In this system, the pion from a two-body decay has a unique momentum of 193 MeV/c, while an electron from a β decay can have a momentum between 0 and 230 MeV/c. We retain all events with a momentum so computed which is smaller than 170 MeV/c. In order to improve our measuring resolution, we remeasure all retained candidates and reapply the same procedure. Half of the exposure was treated this way.

C. Automatic Scan and Measurement with a Flying Spot Digitizer

A fraction of the film (4%) was processed through the Columbia University "Flying Spot Digitizer" (FSD) in an automatic scan and measurement mode,[9] a procedure never previously utilized in a bubble-chamber experiment. This system operated in the following stages:

(i) Track following. The film is digitized by the FSD in two orthogonal scan modes. As the digitization proceeds, tracks are identified and followed in real time with the Marr-Rabinowitz program.[10] Segments of fragmented tracks are linked during the film-stage retrace. All tracks found in each view are output on magnetic tape.

(ii) Event finding. This stage proceeds "offline." Stopping K^- tracks are first identified and matched in three views on the basis of their slope, changing curvature, and heavy ionization. A search is made for tracks originating near the ends of stopping K^- tracks. These are immediately reconstructed in space, along with the K^- track, using three points per track and first-order optics to minimize computation time. The reconstructed tracks are then reassembled and tested for topological and rough kinematic consistency with the hypothesis of Σ production and decay from K^-p at rest.

(iii) Reconstruction and final tests. Tracks of promising events are then reconstructed by the CERN program THRESH. They are then reassembled for a final careful topological and kinematic test of the Σ production and decay hypothesis.

The efficiency of the system for finding and successfully reconstructing a Σ^- decay was about 50%. The events found by the automatic system which were kinematically consistent with the leptonic

TABLE I. Number of events from each source at various stages in the selection procedure.

	Scan 1	Scan 2	Measurement chain	FSD
First measurement			500 000	20 000
Second measurement			25 000	
Precision measurement			6000	1258
Examined by physicist			3000	251
Retained in sample	223	123	183	12
Found by this method only	104	37	119	8

decay of a Σ^- (with center-of-mass decay momentum less than 170 MeV/c) were passed on for treatment in the same manner as leptonic decay candidates found in the two-stage hand scan and measurement of the rest of the film. The sample passed on by the automatic system contained examples of Σ^+ decay and non-Σ events simulating leptonic Σ^- decays. These spurious events were immediately eliminated in the final measurement stage for all leptonic candidates described below.

IV. FINAL SELECTION

All Σ^- leptonic decay candidates thus selected were remeasured on high-precision film-plane digitizing machines, and once more reconstructed and subjected to the kinematical cut described above. In addition we retained only events for which the laboratory momentum of the decay track was less than 170 MeV/c, which for a pion corresponds to a specific ionization 1.6 times minimum. All candidates surviving the above procedure were examined by physicists who separated electrons from pions and muons by visually estimating the bubble density of the track. The few events for which visual identification was ambiguous were measured through a rapid bubble counter. Any event which was still not clearly an electron was discarded for the subsequent analysis. All events accepted for the final analysis were subject to the following cuts:

(1) Fiducial volume.

(2) The c.m. electron momentum, as well as the laboratory value, are required to be less than 170 MeV/c.

(3) $l_{\Sigma^-} \geq 0.1$ cm to ensure positive identification of Σ^- β decay.

(4) $l_{\Sigma^-} \leq 1.0$ cm to eliminate possible Σ^--p interactions.

A total of 393 events survived these cuts. Table I gives the number of events found by each method, as well as the number of events surviving the various stages of the measurement chain.

V. NEUTRON DETECTION AND BACKGROUND

A determination of $|g_A/g_V|$ requires knowledge about the distributions of the nonindependent variables: T_n^*, the c.m. kinetic energy of the neutron, or $\cos\theta_{e\nu}^*$, the c.m. electron-neutrino angular correlation. These variables are known only for events in which the neutron momentum can be determined from an observed n-p scatter in the bubble chamber. Approximately 10% of the neutrons will scatter in 15 cm of liquid hydrogen with a visible recoil proton. There is, however, a large number of recoils in each frame, due to a large neutron flux associated with the beam. We scan for and measure all recoils within 15 cm of the Σ^- decay vertex, and find an average of three per event, 30 times the number of truly associated recoils. True recoils can be separated out of this background by using the kinematical constraint which follows from energy and momentum conservation applied to the chain of processes $\Sigma^- \to ne^-\nu$, $np \to np$. In order to improve the power of such constraint, we imposed the following restrictions on the events:

(1) $l_n \leq 14$ cm,

(2) $l_p \cos\lambda_p \geq 0.2$ cm,

where l_n is the length of the neutron path from the Σ^- decay vertex to the n-p scattering point, l_p is the length of the proton recoil, and λ_p its dip angle in the chamber. The first restriction guarantees a uniform neutron detection efficiency while the second ensures a good measurement of recoil angle and momentum.

The neutron momentum can be computed both at the decay vertex and at the n-p scattering vertex. The difference between these two values vanishes for a true scattering event and ranges over a broad interval for the background events, possibly having no physical solution at all. Figure 1(a) gives the distribution of the difference between the two computed momenta for 241 events. A peak is clearly

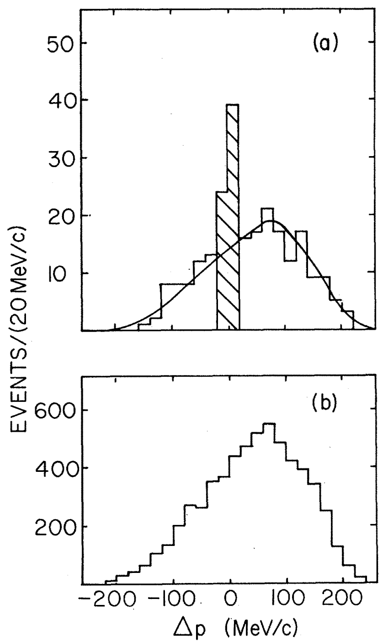

FIG. 1. (a) Distribution in $\Delta p = p_n^{\text{scatt}} - p_n^{\text{decay}}$, the difference in neutron momentum computed at the n-p scatter vertex and at the Σ^- decay vertex, for the actual data. The solid curve is a smooth fit to the background data shown in Fig. 1(b), normalized in the region $50 \leq |\Delta p| \leq 250$ MeV/c. The events in the cross-hatched region are used in the analysis. (b) The same distribution for background simulated by associating each event with recoils from other frames.

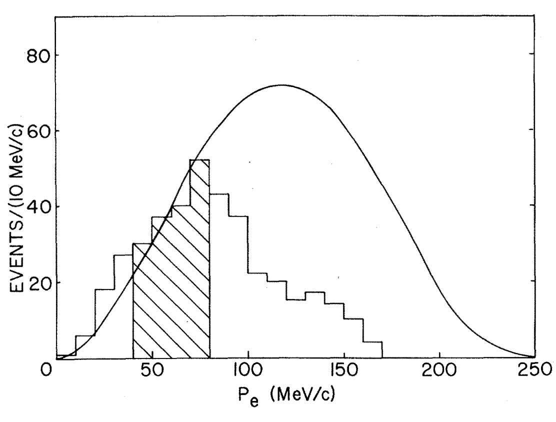

FIG. 2. Distribution in momentum of the electron in the laboratory. The smooth curve gives the expected distribution for $g_A/g_V = 0.30$, but varies little with the assumed value of g_A/g_V. The histogram represents the actual data. The smooth curve has been normalized so as to have the same number of events as the histogram in the cross-hatched region, $40 \leq p_e < 80$ MeV/c. The excess of events in the region $p_e < 40$ MeV/c can be attributed to the decays $\Sigma^- \rightarrow \Lambda^0 e^- \nu$ followed by $\Lambda^0 \rightarrow n\pi^0$. These events, which will not have a true scatter, represent part of our background and are accounted for in our background calculation.

visible at $\Delta p = 0$ and we interpret it as due to n-p scattering events with the neutron coming from the nearby Σ^- decay. We define as "good events" those for which $|p_n^{\text{scatt}} - p_n^{\text{decay}}| \leq 20$ MeV/c, the cross-hatched region in Fig. 1(a).

Because of the rather poor signal-to-noise ratio, it is necessary to better understand the backgound. To do this we have associated, with each leptonic decay, recoils from a large number of other frames, and have performed the same calculations. Figure 1(b) shows a histogram of the difference between computed momenta for this simulated background. Normalizing these two histograms in the region $50 \leq |\Delta p| \leq 250$ MeV/c, we es-

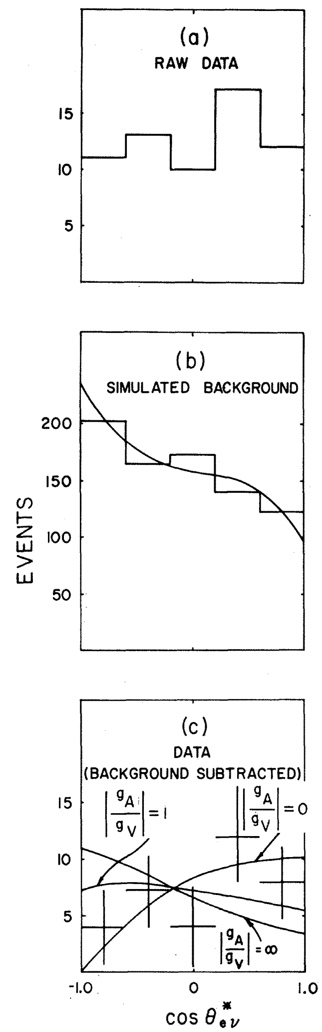

FIG. 3. (a) Distribution in cos $\theta_{e\nu}^*$ for the 63 events with $|\Delta p| \leq 20$ MeV/c. (b) The same distribution for simulated background events with $|\Delta p| \leq 20$ MeV/c. (c) The same distribution for the 36 events after background subtraction. The smooth curves represent expected distributions for $|g_A/g_V| = 0$, 1, and ∞.

timate that 27±6 of our 63 events in the region $|\Delta p| \leq 20$ MeV/c are truly background events.

VI. DETERMINATION OF $|g_A/g_V|$

In order to determine the ratio $|g_A/g_V|$ from the selected sample of Σ β decays, it is in principle necessary to know the momentum dependence of the electron and neutron detection efficiencies.

Our electron efficiency as a function of electron momentum was found by comparing the spectrum of observed events with the expected distribution, which can be treated as independent of $|g_A/g_V|$ within the limits of accuracy of this experiment. Figure 2 shows a comparison of the observed and expected spectra. The neutron detection efficiency, as a function of neutron momentum, was determined by measuring more than 1000 two-body Σ^- decays for associated recoils in the same manner as was used for the β decays.

For a two-body decay, the neutron direction and momentum can be uniquely predicted from the observed charged decay products. In addition, the neutron momentum from such decays spans very closely the same interval as neutrons from three-body decays. This efficiency thus takes into account the varying n-p scattering cross section and any possible scanning biases. These efficiencies were incorporated into a Monte Carlo program, and the expected distribution $I(\cos\theta^*_{e\nu}, |g_A/g_V|)$ was found and parametrized, assuming a matrix element of the form

$$\bar{u}_n(g_V\gamma_\mu - g_A\gamma_\mu\gamma_5)u_\Sigma \bar{u}_e\gamma^\mu(1+\gamma_5)u_\nu .$$

Neglecting other contributions to the decay amplitude as well as any explicit momentum-transfer dependence of the parameters, g_A and g_V are well justified by the limited statistical accuracy of our data.

Figure 3(a) shows the distribution in $\cos\theta^*_{e\nu}$ for the 63 selected events. The expected distribution for the background, $B(\cos\theta^*_{e\nu})$, is obtained from the simulated events for which $|\Delta p| \leq 20$ MeV/c, and is shown in Fig. 3(b). This distribution is *not* uniform; in fact its slope is more negative than would be expected for a pure axial-vector current. Figure 3(c) is a histogram of the data with the background subtracted, indicating a predominantly vector current.

In order to best estimate $|g_A/g_V|$, the method of maximum likelihood has been used. The likelihood of the 63 observed events is computed using the distribution in $\cos\theta^*_{e\nu}$ discussed previously, the measured background-to-signal ratio, $\epsilon_b = \frac{27}{36}$, and the expected background distribution, $B(\cos\theta^*_{e\nu})$. Since the background recoils are distributed nearly uniformly throughout the chamber, the number observed at a given distance from the Σ^- decay vertex increases as the square of this distance (the length of the supposed neutron), while the probability of producing a genuine recoil at a given distance is nearly independent of this distance. We therefore write the probability of observing the ith event as

$$P_i = \left[\left(\frac{1}{L_{\max}}\right) I\left(\cos\theta^*_i, \left|\frac{g_A}{g_V}\right|\right) + \epsilon_b\left(\frac{4\pi L_i^2}{4/3\pi L_{\max}^3}\right) 3(\cos\theta^*_i)\right] \Big/ (1+\epsilon_b) .$$

A likelihood fit using this function gives the result[11]

$$|g_A/g_V| = 0.29^{+0.28}_{-0.29} .$$

VII. SENSITIVITY TO EXPERIMENTAL UNCERTAINTIES

As was stated in the beginning, the electron-neutrino correlation is not unique in determining the ratio $|g_A/g_V|$. One could equally perform a maximum-likelihood calculation using the recoil momentum or most correctly the joint distribution function in both $\theta_{e\nu}$ and p_n.

Since, however, p_n and $\theta_{e\nu}$ are not completely independent, it turns out that the error in determining $|g_A/g_V|$ is essentially the same whether one uses only $\theta_{e\nu}$, only p_n, or both. The three possibilities are, however, differently sensitive to distortions of the electron spectrum. In the present experiment, the electron efficiency is poorly determined, being based on 393 examples of Σ^- leptonic decays found in our experiment. We have thus investigated the sensitivity of the result for the ratio $|g_A/g_V|$ to the actual knowledge of the electron detection efficiency.

This has been done by obtaining new values for the distribution function $I(\cos\theta^*_{e\nu}, |g_A/g_V|)$ assuming electron detection efficiency which deviates grossly from the one used before. A new value was obtained for $|g_A/g_V|$ which differed from the one quoted above by 0.02 or ~7% of the error of our determination. The same procedure used for the neutron recoil spectrum case gave results which changed, for the same change in the electron efficiency, by 70% of the error, while when using the combined information of $\theta_{e\nu}$ and p_n, we obtained an intermediate result, or approximately 35% of the error.

We thus conclude that our analysis is the least sensitive to an exact knowledge of the electron detection efficiency and by the same reason is completely insensitive to the small dependence of the electron spectrum on the actual value of $|g_A/g_V|$.

TABLE II. Most recent results of measurements of g_A/g_V for the decay $\Sigma^- \to n e^- \bar{\nu}$.

Reference	Group	Result	Method
This experiment		$\lvert g_A/g_V \rvert = 0.29^{+0.28}_{-0.29}$	n–p scatter
12	Maryland	$\lvert g_A/g_V \rvert = 0.23 \pm 0.16$	n–p scatter
13	Heidelberg	$\lvert g_A/g_V \rvert = 0.37^{+0.26}_{-0.19}$	n–p scatter
4	U.C.R.L.	$g_A/g_V = +0.19^{+0.20}_{-0.17}$	electron asymmetry from polarized Σ^-
5	Yale, U. Mass.	$g_A/g_V = -0.33^{+0.39}_{-0.85}$	electron asymmetry from polarized Σ^-
14	Heidelberg	$g_A/g_V = +0.33$	fit to Cabibbo parameters

[a]Note: The sign convention for g_A/g_V corresponds to a value of $g_A/g_V = -1.23$ for neutron β decay.

In addition, we have checked that varying the amount and shape of the background distribution, and the electron and neutron detection efficiencies, within their respective errors, changes the peak and width of the likelihood function by an amount small relative to our quoted error.

The results of these experiments are in good agreement with those reported by other groups,[12,13,4,5] and with the most recent fit[14] to the Cabibbo parameters, as summarized in Table II.

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