Relative Sign of Strangeness-Changing Axial-Vector and Vector Currents*

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(Received 18 June 1973)

The determination of the relative sign of strangeness-changing hadronic axial-vector and vector currents is considered within the framework of V,A theory and the experimental information on hyperon beta decays, in particular the spin correlation parameters for $\Lambda \to p e \nu$. If the sign of the Λ polarization is accepted as obtained from nonleptonic decay experiments, the $V+A$ form of the current is excluded. If the polarization sign is assumed to be the opposite, a necessary condition for the consistency of the correlation parameters for $\Lambda \to p e \nu$ with V,A theory is the presence of very large tensor and/or axial-tensor form factors. Explicit fits to the data allowing for such form factors have very small probabilities. It is concluded that the consistency of the experimental results with V,A theory strongly supports the polarization sign as inferred from $\Lambda \to p\pi$, and hence, the $V-A$ form of the $|\Delta S| = 1$ current.

I. INTRODUCTION

Recently there have been many attempts to extend gauge field-theory models of weak and electromagnetic interactions of leptons by the inclusion of hadrons. Yang-Mills-type theories with a charged current generally also involve the neutral current obtained from the commutator of the charged one with its Hermitian conjugate. At this point, there arises the problem of how to avoid the appearance of strangeness-changing neutral hadronic currents because the corresponding transitions are strongly suppressed.[1]

One simple and economical way of preventing the appearance of neutral $|\Delta S|=1$ currents in lowest order is to postulate that the $|\Delta S|=1$ part of the charged hadron current is of the form $V+A$, in contrast to the established $V-A$ form of the $\Delta S=0$ current.[2] This interesting possibility has recently been considered by several people.[3]

In terms of quark currents, we would then have a hadronic current of the form

$$\cos\theta[\bar{\mathcal{P}} i\gamma_\alpha(1+\gamma_5)\mathfrak{N}] \quad \text{for } \Delta S=0\,, \tag{1}$$

$$\sin\theta[\bar{\mathcal{P}} i\gamma_\alpha(1-\gamma_5)\lambda] \quad \text{for } |\Delta S|=1\,, \tag{2}$$

where $(\mathcal{P},\mathfrak{N},\lambda)$ is the usual quark triplet. This current differs from the conventional universal one[4] only by the reversed sign of the strangeness-changing axial-vector part.

In this paper we consider the determination of the relative sign of $|\Delta S|=1$ hadronic axial-vector and vector currents within the framework of V,A theory and the available information on leptonic decays of hyperons.

II. POLARIZED HYPERON DECAY

The relative sign of the axial-vector and vector currents is only indirectly reflected in the properties of the observable quantities in leptonic hyperon decays, which may be expressed in terms of the invariant form factors f_i and g_i. In order to define our notation, we write the matrix element for $A\to B+e+\bar{\nu}$ in the form

$$M=\langle B|V_\alpha+A_\alpha|A\rangle \bar{e} i\gamma_\alpha(1+\gamma_5)\nu\,, \tag{3}$$

with

$$\begin{aligned}\langle B|V_\alpha|A\rangle &= \bar{u}_B(i\gamma_\alpha f_1 + i\sigma_{\alpha\beta}q_\beta f_2/M_A)u_A\,,\\ \langle B|A_\alpha|A\rangle &= \bar{u}_B(i\gamma_\alpha\gamma_5 g_1 + i\sigma_{\alpha\beta}q_\beta\gamma_5 g_2/M_A)u_A\,,\end{aligned} \tag{4}$$

and $q=p_A-p_B=p_e+p_\nu$. Contributions proportional to the electron mass have been omitted, and we neglect the q^2 dependence of the form factors. Also radiative corrections are not considered.

It will turn out to be useful for our discussion to introduce the operation of "A/V sign reversal" as the change of sign of the $|\Delta S|=1$ axial-vector current. It implies, of course, a corresponding sign change of all form factors g_i appearing in the matrix elements of this axial-vector current. From the general expressions[5] for the hyperon beta-decay rate and the electron-neutrino correlation $A_{e\nu}$, we see that they are invariant under A/V sign reversal. On the other hand, the proton spin correlation[6] A_p changes sign, as does the sum of the electron and neutrino spin correlations[6] A_e+A_ν. [For definiteness, we think here in terms of the decay $\Lambda\to pe\nu$.] We find that any sensitive attempt to distinguish between $V+A$ and $V-A$ interactions must involve baryon polarization information. At present, the process $\Lambda\to pe\nu$ is the only hyperon beta decay for which precise polarized data exist.

Table I contains a summary of the data on the decay $\Lambda\to pe\nu$ in terms of the quantities which are directly measured in the experiments.[6] There is good agreement on the values for the branching

TABLE I. Summary of experimental results on $\Lambda \to pe\nu$ (see Ref. 6).

Experiment	Ref.	Events Total	Events Analyzed	Polarization	A_ν	A_e	A_p	$A_{e\nu}$	$10^3 \times$(branching ratio)
Maryland	13	1089	608					0.01 ± 0.07	0.807 ± 0.046
CERN-Heidelberg	14	1078	817	0.75 ± 0.03	0.89 ± 0.08	0.15 ± 0.09	-0.51 ± 0.09	0.07 ± 0.085	0.84 ± 0.04
Lindquist *et al.*	15	504	409	0.85 ± 0.06	0.75 ± 0.11	0.09 ± 0.11	-0.55 ± 0.11	-0.08 ± 0.10	0.83 ± 0.10
Baggett *et al.*	16	416	352					0.00 ± 0.08	
Carnegie-Mellon	17		271					0.10 ± 0.13	
Canter *et al.*	18	198	141					0.00 ± 0.14	0.78 ± 0.09
Baglin *et al.*	19		102					-0.21 ± 0.24	0.75 ± 0.12 [b]
Barlow *et al.*	20		84	0.60 ± 0.10		0.06 ± 0.19			
Ely *et al.*	21	150	59					< 0.05 [a]	0.79 ± 0.13 [b]
Lind *et al.*	22		22	0.91 ± 0.10	0.74 ± 0.39	0.60 ± 0.35		-0.06 ± 0.34	1.49 ± 0.33 [a,b]
Weighted mean					0.839 ± 0.064	0.134 ± 0.064	-0.526 ± 0.070	0.007 ± 0.037	0.817 ± 0.026
Consistency χ^2/d.f.					1.1/2	2.1/3	0.1/1	2.7/7	0.9/5

[a] Not included in weighted mean.
[b] Corrected for current value of $\Lambda p\pi$/all $\Lambda = 0.642 \pm 0.005$.

ratio and the e-ν correlation, and the two recent experiments with polarized Λ hyperons yield quite definite results for the spin correlation parameters. Therefore, we can use the weighted means and their errors with confidence.

In these experiments, the polarization is calibrated by the nonleptonic decay mode $\Lambda \to p\pi^-$. Thus the polarization, and in particular its sign, is set by the classic measurements of the proton asymmetry parameter[7] α_p by Cronin, Overseth, and Roth[8] which were performed by scattering the decay protons off carbon. It is interesting to note that the sign of the analyzing power of carbon is obtained by comparison with scattering in helium[9] at proton energies sufficiently low (a few MeV) that a phase-shift analysis of the p-He system is considered reliable. In this connection, an ingenious double-scattering experiment resolved the ambiguity between a dominant $P_{1/2}$ and a dominant $P_{3/2}$ interaction in favor of the latter.[10] The two choices would, of course, give opposite signs for the low-energy analyzing power.

In Table I and in the following section, we adopt the sign of the Λ polarization as inferred by the method described above. Later, in Sec. IV, we ask to what extent this sign can be obtained as a self-consistency condition on the beta-decay data alone.

III. $V+A$ CURRENT

We now ask to what extent a $V+A$ current of the form (2) can be compatible with the experimental data for hyperon beta decays. In this section, we assume SU(3) symmetry and take matrix elements of the currents using hadron states which are octet eigenstates. The axial-vector form factor g_1 for the various decays is then given in terms of two reduced matrix elements F and D. The relevant expressions are listed in Table II. From correlation experiments[2] for $n \to pe\nu$ we obtain $F+D = 1.25$. In extracting the ratio g_1/f_1 from the corresponding experimental results for $\Lambda \to pe\nu$, we must specify the assumptions made about tensor, and, in particular, pseudotensor form factors. Because the energy release for $\Lambda \to pe\nu$ and other hyperon decays is considerably larger than for neutron decay, the contribution of these terms can be relevant. Since we assume SU(3) symmetry, we expect $g_2 = 0$ provided the interaction contains only first-class currents which are normal under time reversal (T normal).[11,12] The available data from all Λ beta-decay experiments[13-22] then give roughly $g_1/f_1 \simeq 0.7$, with f_2/f_1 being of order unity. Hence we have for the $V+A$ interaction $F + \frac{1}{3}D \simeq -0.7$.

With $V+A$ values for F and D obtained in this

TABLE II. Comparison of D and F values for $V-A$ and $V+A$ currents.

	$V-A$		$V+A$	
Decay	g_1/f_1 formula [a]	g_1/f_1 value	g_1/f_1 formula [a]	g_1/f_1 value
$n\to pe^-\nu$	$F+D$	$\{1.25\}$ [b]	$F+D$	$\{1.25\}$ [b]
$\Lambda\to pe^-\nu$	$F+\frac{1}{3}D$	$\{0.25$ to $0.75\}$ [b]	$-(F+\frac{1}{3}D)$	$\{0.25$ to $0.75\}$ [b]
$\Sigma^-\to ne^-\nu$	$F-D$	-1.75 to -0.25	$-(F-D)$	3.25 to 4.75
$\Sigma^\pm\to\Lambda e^\pm\nu$	$(\frac{2}{3})^{1/2}D$	1.22 to 0.66	$(\frac{2}{3})^{1/2}D$	1.84 to 2.45
	$D=1.50$ to 0.75		$D=2.25$ to 3.00	
	$F=-0.25$ to 0.50		$F=-1.00$ to -1.75	

[a] For $\Sigma^\pm\to\Lambda e^\pm\nu$, the listed expression is $g_1/\cos\theta$, since the Clebsch-Gordan coefficient for the f_1 amplitude vanishes.

[b] These values are input data. See Refs. 2 and 15 and the averages in Table I.

way from $n\to pe\nu$ and $\Lambda\to pe\nu$, we can calculate the branching ratios for the reactions $\Sigma^-\to ne^-\nu$ and $\Sigma^-\to\Lambda e^-\nu$. They turn out to be too large by about *two* orders of magnitude for the first decay, and *one* order of magnitude for the second.

Although in gauge theories we do not expect to have contributions to the basic currents which are divergences of tensor or pseudotensor densities, we want to be more general and thus more conservative when interpreting the data, and hence we impose no such restrictions. Then we can also have nonvanishing pseudotensor form factors. A second-class, T-normal axial-vector current can give rise to a finite g_2 form factor even in the SU(3) limit.[12]

Without second-class currents, there can still be induced pseudotensor form factors if SU(3) is broken and if the transition is between states which do not belong to the same isospin multiplet.[11] We can allow for such effects, provided the SU(3)-symmetry breaking is sufficiently small that it does not seriously affect the computation of the axial-vector form factors using SU(3) Clebsch-Gordan coefficients.

In Table II, we have given the maximum range for g_1/f_1 admitted by the correlation data for $\Lambda\to pe\nu$ (world averages). The uncertainty in g_1/f_1 then arises from the possible variation of g_2/f_1 and f_2/f_1 as discussed above. With this information as input, we find for the $V+A$ current

$$D\gtrsim 2.25 \text{ and } F\lesssim -1.00\,.$$

In the allowed approximation, where the rates are proportional to $|f_1|^2+3|g_1|^2$, these values predict branching ratios which are at least 23 times too large for $\Sigma^-\to ne^-\nu$ and 9 times too large for $\Sigma^-\to\Lambda e^-\nu$. However, in both cases we may consider the possibility of cancellations due to unusually large pseudotensor and, to a lesser extent, tensor form factors.

We recall the expression for the rate of $A\to Be\nu$ in terms of the form factors. Up to second order in $\beta\equiv M_A-M_B/M_A$, it is proportional to[5]

$$R=(1-\tfrac{3}{2}\beta)[(1+\tfrac{6}{7}\beta^2)|f_1|^2+\tfrac{4}{7}\beta^2|f_2|^2+\tfrac{6}{7}\beta^2\operatorname{Re}f_1f_2^*+3(1+\tfrac{4}{7}\beta^2)|g_1|^2+\tfrac{12}{7}\beta^2|g_2|^2-4\beta\operatorname{Re}g_1g_2^*]\,. \tag{5}$$

With the form factors f_1 and g_1 fixed, this expression has a minimum value of

$$R_{\min}=(1-\tfrac{3}{2}\beta)[(1+\tfrac{15}{28}\beta^2)|f_1|^2+\tfrac{2}{3}(1+\tfrac{18}{7}\beta^2)|g_1|^2] \tag{6}$$

for

$$g_2=\tfrac{7}{6}\beta^{-1}g_1 \text{ and } f_2=-\tfrac{3}{4}f_1\,.$$

With $R_{\min}$ we still obtain a rate for $\Sigma^-\to ne^-\nu$ ($\Sigma^-\to\Lambda e^-\nu$) which is approximately 4 (2) times too large. We note that the rate for $\Sigma^-\to ne^-\nu$ is known[23] to better than 6%, and that for $\Sigma^-\to\Lambda e^-\nu$ to better than 12%.

We conclude that, using the sign of the Λ polarization obtained from $\Lambda\to p\pi$ decay, we cannot accommodate a $V+A$ current within the framework of a universal SU(3) scheme.

IV. REVERSED Λ POLARIZATION

While we do not doubt that the sign of the Λ polarization in the beta-decay experiments is properly inferred,[24] the discussion in Sec. II has shown it to be a delicate matter. Therefore it is of interest to see whether this polarization sign, and hence the sign of A/V, can be obtained from a self-consistency condition on the beta-decay data alone.

In order to see the difficulties which arise if one tries to fit the correlation parameters in Λ beta decay under the assumption of the "wrong" polarization sign, we find it convenient to study a specific combination of the spin correlation coefficients A_e and A_ν and the electron-neutrino correlation $A_{e\nu}$. The combination "Σ" has been introduced in Ref. 25. It is essentially given by

$$\Sigma \simeq [(A_\nu - A_e) - (1 - A_{e\nu})](1 + A_{e\nu})^{-1}. \quad (7)$$

The function Σ vanishes in the allowed approximation. Hence one expects *a priori* $\Sigma \ll 1$. We see that the quantity Σ is useful for our purposes because under A/V sign reversal the difference $A_\nu - A_e$ and the electron-neutrino correlation $A_{e\nu}$ do not change sign. On the other hand, under polarization reversal, all spin correlations change sign, while $A_{e\nu}$ does not.

Experimentally, we find

$$\Sigma = -0.09 \pm 0.06,$$

using the average values from Table I and the conventional sign of the polarization. For the other choice of the polarization sign, we obtain

$$\Sigma = -1.11 \pm 0.06.$$

Let us now express the function Σ in terms of the form factors:

$$\Sigma \simeq \tfrac{1}{3}\beta\left(1 + 2\,\mathrm{Re}\frac{f_1 f_2^* + g_1 g_2^*}{|f_1|^2 + |g_1|^2} - \beta\frac{\frac{5}{7}|f_2|^2 + \frac{11}{7}|g_2|^2}{|f_1|^2 + |g_1|^2}\right), \quad (8)$$

where

$$\tfrac{1}{3}\beta \simeq 0.05,$$

and where we have retained only those terms of order β^2 which are relevant for our purpose.

To obtain $\Sigma \simeq -1$, we see from Eq. (8) that, in the dominant first term of order β, the combination

$$\mathrm{Re}\frac{f_1 f_2^* + g_1 g_2^*}{|f_1|^2 + |g_1|^2}$$

must be large and negative: roughly -10. For example, with $g_2 = 0$ and $|g_1| \lesssim |f_1|$, this would imply

$$\frac{f_2}{f_1} \simeq -10.$$

We see that the "wrong" choice of the polarization sign would require tensor and/or pseudotensor form factors which are larger in magnitude than the direct vector or axial-vector couplings. In gauge theories of weak and electromagnetic interactions, we generally have only vector and axial-vector currents. In particular, there are no second-class terms present.[26] As is well known, currents which are divergences of tensor densities would ruin the renormalizability of the theory at the quark level, destroying one of its assets. Hence, in this framework, we must view the tensor form factors in the hadronic matrix element as *induced* ones.

In the hadronic matrix elements of the electromagnetic current, we have induced tensor form factors which are roughly of the same order of magnitude as the vector terms. [Here we use a normalization analogous that employed in Eq. (4).] With the conserved-vector-current hypothesis, we can say the same for the matrix elements of the strangeness-conserving weak hadronic current. With the assumption of a $V+A$ coupling for strangeness-changing weak interactions, we find from the measured spin correlations for Λ beta decay that corresponding induced terms are required as a necessary condition for consistency which are several times larger in magnitude than the direct vector and pseudovector form factors. It would appear then that the current structure at the constituent level is far removed from the structure of the physical matrix elements, and it would be an important task of the theory to explain the large induced form factors.

Besides these relatively general and qualitative considerations, we can, of course, ask for a "fit" of the data with the unconventional polarization sign in terms of the ratios g_1/f_1, g_2/f_1, and f_2/f_1 as free parameters. Using the weighted means of the four correlation parameters as listed in Table I, but with the signs reversed for A_e, A_ν, and A_p, we find that the "best fit" (i.e., χ^2 minimum) occurs at a χ^2 of 39 for one degree of freedom.[27] At the minimum, the form-factor ratios are

$$\frac{g_1}{f_1} = -0.25, \quad \frac{f_2}{f_1} = -8.0, \quad \frac{g_2}{f_1} = 0.4, \quad (9)$$

and the correlations are

$$A_\nu = -0.46, \quad A_e = -0.21,$$

$$A_p = 0.57, \quad A_{e\nu} = 0.06.$$

We see that, in addition to having a problematically large value for the amount of f_2, we cannot obtain a reasonable fit to the Λ beta-decay data within the framework of a V,A theory if we require the unconventional sign for the Λ polarization.[28]

V. CONCLUSIONS

(1) If the sign of the Λ polarization is accepted as determined by the analysis of $\Lambda \to p\pi$ decay and the measurements of proton-helium scattering, we find that the $V+A$ form of the hadronic current is not compatible with the experimental information on hyperon beta decays. Here we have assumed the usual universal SU(3) scheme except that the sign of the axial-vector current for $|\Delta S| = 1$ has been reversed. In contrast, within the same framework, the $V-A$ current is relatively consistent with the data.

(2) If the Λ polarization is assumed to be opposite to the usually accepted one, we see from an analysis of the correlation parameters in Λ beta decay that tensor and/or axial-tensor form factors are required as a necessary condition for a solution.

These form factors are larger in absolute value than the vector form factors by an order of magnitude. They are implausible from the point of view of gauge theories. Furthermore, with the unconventional polarization sign, fits to the measured Λ beta-decay correlations in the framework of a V, A theory have very small probabilities.

We conclude that the consistency of the measured correlation parameters for $\Lambda \to pe\nu$ with the V, A theory strongly supports the polarization sign as inferred from $\Lambda \to p\pi$ decays, and hence the $V-A$ form of the hadronic $|\Delta S|=1$ current.

ACKNOWLEDGMENTS

We have benefited from discussions with several colleagues, in particular with J. W. Cronin, S. L. Glashow, and J. M. Watson.

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*Work supported in part by the National Science Foundation under Contracts No. NSF GP 32904X and No. NSF GP 32534.

[1]See, for example, J. H. Klems, R. H. Hildebrand, and R. Steining, Phys. Rev. D 4, 66 (1971); A. R. Clark *et al.*, Phys. Rev. Lett. 26, 1667 (1971); W. C. Carithers *et al.*, Bull. Am. Phys. Soc. 18, 638 (1973); G. Ang *et al.*, Z. Phys. 228, 151 (1969).

[2]M, T. Burgy, V. E. Krohn, T. B. Novey, G. R. Ringo, and V. L. Telegdi, Phys. Rev. 120, 1829 (1960); C. J. Christensen, V. E. Krohn, and G. R. Ringo, Phys. Rev. C 1, 1693 (1970) and references therein; B. F. Erozolimskii *et al.*, Zh. Eksp. Teor. Fiz. Pis'ma Red. 13, No. 7 (1971) [JEPT Lett. 13, 252 (1971)].

[3]For example, J. Pati and A. Salam, private communication to R. Oehme (summer 1972); H. Georgi and S. L. Glashow, Phys. Lett. 44B, 191 (1973).

[4]N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963); Z. Maki, M. Nakagawa, and S. Sakata, in *Proceedings of the 1962 International Conference on High-Energy Physics at CERN,* edited by J. Prentki (CERN, Geneva, 1962), p. 663; M. Gell-Mann and M. Lêvy, Nuovo Cimento 16, 705 (1960). In the usual universal SU(3) scheme with a $V-A$ interaction, the $|\Delta S|=1$ amplitudes for semileptonic decays are multiplied by $\sin\theta$ (θ is the Cabibbo angle), where θ is the same for vector and axial-vector current matrix elements. Except for this angle, the assumed SU(3) symmetry fixes the $|\Delta S|=1$ form factors in terms of the reduced matrix elements, which in turn can be determined in principle from the $\Delta S=0$ decays. In the universal SU(3) scheme with $V-A$ structure for $\Delta S=0$ and $V+A$ structure for $|\Delta S|=1$ semileptonic interactions, the vector parts of $|\Delta S|=1$ amplitudes are again multiplied by $\sin\theta$, but the axial-vector parts have the factor $-\sin\theta$. In other words, if we would distinguish between Cabibbo angles θ_V for vector and θ_A for axial-vector interactions, we could write $\theta_V=-\theta_A=\theta$.

[5]See, for example, J. M. Watson and R. Winston, Phys. Rev. 181, 1907 (1969); V. Linke, Nucl. Phys. B12, 669 (1969); A. Garcia, Phys. Rev. D 3, 2638 (1971).

[6]We define the spin correlation parameters used in the text in the usual way, $A_i P_\Lambda = 2[N(i\uparrow) - N(i\downarrow)]/[N(i\uparrow) + N(i\downarrow)]$, where decay product i is $\uparrow$ or $\downarrow$ as the projection of its momentum along the Λ polarization vector is positive or negative, respectively.

[7]The proton asymmetry parameter α_p for $\Lambda \to p\pi$ decay is positive if more protons are emitted along the Λ spin direction than opposite to it; α_p is then also the helicity of protons from unpolarized $\Lambda p\pi$ decay. The currently accepted value is $\alpha_p = +0.645 \pm 0.016$.

[8]J. W. Cronin and O. E. Overseth, Phys. Rev. 129, 1795 (1963); O. E. Overseth and R. F. Roth, Phys. Rev. Lett. 19, 391 (1967); W. E. Cleland *et al.*, Nucl. Phys. B40, 221 (1972).

[9]L. Marshall and J. Marshall, Phys. Rev. 98, 1398 (1955); M. L. Brinkworth and B. Rose, Nuovo Cimento 3, 195 (1956). Supporting evidence for the accepted sign of the carbon analyzing power comes from a recent measurement of the spin correlation parameters A, R, and P performed by scattering $\pi^\pm$ from a polarized target and analyzing the recoil proton polarization by a second scattering off carbon. The sign which is found for A agrees with the expected nonflip dominance. The internal consistency of such data is also quite sensitive to the sign of the carbon analyzing power. See A. De Lesquen *et al.*, Phys. Lett. 40B, 277 (1972).

[10]M. Heusinkveld and G. Freier, Phys. Rev. 85, 80 (1952).

[11]L. Wolfenstein, Phys. Rev. 135, B1436 (1964); M. Ademollo and R. Gatto, Phys. Rev. Lett. 13, 264 (1964); H. Primakoff, in *Lectures on Elementary Particles and Quantum Field Theory,* edited by S. Deser, M. Grisaru, and H. Pendleton (M.I.T. Press, Cambridge, Mass., 1970), Vol. 2, p. 269; these papers contain further references.

[12]R. Oehme, Phys. Lett. 38B, 532 (1972).

[13]G. A. Snow, private communication; J. E. Maloney and B. Sechi-Zorn, Phys. Rev. Lett. 23, 425 (1969).

[14]K. H. Althoff *et al.*, Phys. Lett. 37B, 531 (1971); K. H. Althoff *et al.*, *ibid.* 37B, 535 (1971); K. H. Althoff *et al.*, *ibid.* 43B, 237 (1973). The full sample of 1078 events was employed in the direct laboratory determination of A_e, A_p, and the branching ratio, and in a Monte Carlo–based analysis of a laboratory angular correlation to obtain $A_{e\nu}$. Time-of-flight data were used for the restricted sample of 817 events to estimate K^+ and p^+ momenta. A_ν was then obtained from this subsample by a detailed comparison with the Monte Carlo simulation.

[15]J. Lindquist *et al.*, University of Chicago, Enrico Fermi Institute Report No. EFI-72-32, 1972 (unpublished); and in *Proceedings of the XVI International Conference on High Energy Physics, Chicago-Batavia, Ill., 1972,* edited by J. D. Jackson and A. Roberts (NAL, Batavia, Ill., 1972); J. Lindquist *et al.*, Phys. Rev. Lett. 27, 612 (1971).

[16]M. Baggett *et al.*, Z. Phys. 249, 279 (1972).

[17]C. T. Murphy, private communication.

[18]J. Canter *et al.*, Phys. Rev. Lett. 26, 868 (1971).
[19]C. Baglin *et al.*, Nuovo Cimento 35, 977 (1965).
[20]J. Barlow *et al.*, Phys. Lett. 18, 64 (1965).
[21]R. P. Ely *et al.*, Phys. Rev. 137, B1302 (1965); R. P. Ely *et al.*, Phys. Rev. 131, 868 (1963).
[22]V. G. Lind *et al.*, Phys. Rev. 135, B1483 (1964).
[23]Averages obtained from *Review of Particle Properties* [Particle Data Group, Phys. Lett. 39B, 1 (1972)].
[24]The "accepted" sign corresponds to Λ's from $\pi^- p \to \Lambda K^0$ in the vicinity of 1025 MeV/c being polarized along the direction $\hat{\Lambda}\times\hat{\pi}$, i.e., the excess of protons from $\Lambda p\pi$ decay is seen along this direction (see also Ref. 7).
[25]R. Oehme, R. Winston, and A. Garcia, Phys. Rev. D 3, 1618 (1971).
[26]For example, in the quark model we can write a $|\Delta S|=1$ tensor density in the form $(\bar{\mathcal{P}}\sigma_{\alpha\beta}\lambda)$. The corresponding vector current density $\partial_\beta[\bar{\mathcal{P}}(x)\sigma_{\alpha\beta}\lambda(x)]$ is first-class. A pseudotensor density is given by $(\bar{\mathcal{P}}\sigma_{\alpha\beta}\gamma_5\lambda)$, giving rise to the second-class current density $\partial_\beta[\bar{\mathcal{P}}(x)\sigma_{\alpha\beta}\gamma_5\lambda(x)]$. See Ref. 12.
[27]This has a χ^2 probability of 10^{-10}. Several heuristic attempts were made to include effects of correlations between A_ν, A_e, and A_p as well as influences of possible systematic errors in the data. Minima always occurred at essentially the same place in the parameter space, and in no case could we obtain a χ^2 probability better than 10^{-5}.
[28]It should be noted that we have used in this section only experimental information about Λ beta decay. Further constraints on exotic solutions like (9) could be obtained by assuming SU(3) symmetry and using additional information from other decays. Here we do not pursue this matter.

PHYSICAL REVIEW D VOLUME 8, NUMBER 7 1 OCTOBER 1973

Radiative Corrections to Deep-Inelastic Neutrino-Nucleon Scattering*

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(Received 17 May 1973)

A simple parton model is used to estimate the radiative corrections to neutrino-induced inclusive processes. An application of the resulting expressions to $\nu_\mu + p \to \mu^- + X$ at $E_\nu^{\text{LAB}} = 100$ GeV shows that the muon spectrum is distorted by as much as 10% in some regions.

I. INTRODUCTION

The results from deep-inelastic, inclusive neutrino-nucleon scattering experiments which are in progress or planned for the near future will be an important input for current theoretical work. The effects of radiative corrections must be considered in interpreting these experimental results.[1]

Unfortunately, it is impossible to calculate the radiative corrections to an inclusive process which is controlled by unspecified dynamics. There are two reasons for this. First, the long-wavelength photons are sensitive to changes in the large-scale distribution of electric charges and currents. This information is not available unless the general features of the hadronic final state are specified. Second, the short-wavelength photons are sensitive to details of the current distribution in the interaction region. Again, this information is not available in the absence of a theory for the basic interaction. Thus, in order to estimate radiative corrections, we need a model which specifies the electromagnetic currents in some detail. We will use the parton model.[2]

In this model, the nucleon target is to be viewed as a collection of weakly bound, relatively light point particles. The neutrino is assumed to have a weak interaction with one of these target partons. In the deep-inelastic region, this parton gets a large acceleration, and the leptonic system suffers a large reaction. The other partons are assumed to receive accelerations much smaller than that of the leptonic system or the struck parton.

Classical intuition suggests that the charges which are accelerated the most will make the major contribution to the radiative correction. Thus, we will consider only contributions where the photon is attached to the struck parton or the outgoing muon, and we will sum over the partons incoherently as usual.

This is analogous to the usual practice of calculating radiative corrections by considering only the proton in the target which is struck and then summing incoherently over the protons in the target. This restriction of the number of Feynman graphs is gauge-invariant so long as we ignore the interactions between the partons.

For the purposes of this calculation, we will assume further that the final-state interactions which "dress" the outgoing parton give a jet of outgoing physical particles which have the same charge and essentially the same momentum as the