baryon mass, and W the total c.m. energy. See reference 2 for the kinematically accurate expressions.

[7]One can verify that this formula gives the appropriate Born terms due to baryon exchange, if the lower limit is extended to pick up the delta-function contribution from Imh_l-. We might also mention that the approximations leading to (1) yield equations combining the advantages of the static nucleon theory with those of the fully relativistic theory. Thus one obtains the correct cuts in the variable s but none of the "nuisance" cuts in $W=s^{1/2}$. (At the same time the linear divergence of the static theory is removed.)

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[12]In place of the symbols of reference 5, we prefer to distinguish the various baryons and their resonances by a symbol such as $B_{JP}{}^i(Y,T,T_3)$, where B stands for baryon, i the representation (multiplet) to which the state belongs, J the total angular momentum, P the parity, Y the hypercharge, and T and T_3 the total and third component of isospin. For instance, the third $\pi^- - p$ resonance would be designated $B_{5/2^+}{}^8(1, 1/2, -1/2)$.

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NEUTRINO INTERACTIONS AND A UNITARY UNIVERSAL MODEL*

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We examine in this note some of the knowledge that can be gleaned from intensive studies of neutrino and antineutrino interactions in the energy region slightly above the thresholds for strange-particle and baryon-resonance production, i.e., in the energy region ~1-2 BeV/c. For example, the basic structure of the weak interactions can be simply tested, in large bubble chambers. Feynman and Gell-Mann[1] have proposed the selection rules $\Delta S=0, \Delta I=1$ and $\Delta S=\Delta Q, \Delta I=1/2$ for weak interactions. Proposed tests, using neutrino and antineutrino beams, are suggested.

Test of $\Delta S=\Delta Q$ law.—Let us define a violation parameter $x=\Gamma(\Delta S=-\Delta Q)/\Gamma(\Delta S=+\Delta Q)$. We denote nuclear matter consisting of A nucleons and Z protons by A_Z. In the $|\Delta S|=1$ neutrino reaction in which a hyperon Y of $S=-1$, A-1 nucleons, and n pions are formed, i.e.,

$$\nu+A_Z \to (Y, A-1, n\pi)_{Z+1}+\mu^-, \qquad (1)$$

we note that lepton conservation forces the emission of a negative muon, so the total charge of the strongly interacting system is $Z+1$. Thus, for Reaction (1), we have the selection law $\Delta S=-\Delta Q$. Conversely, in the corresponding antineutrino reaction,

$$\bar{\nu}+A_Z \to (Y, A-1, n\pi)_{Z-1}+\mu^+, \qquad (2)$$

lepton conservation insures that $\Delta S=+\Delta Q$. Clearly, the violation parameter x is the ratio of the cross sections of (1) to (2), $\sigma(1)/\sigma(2)$. For purposes of estimating the experimental sensitivity for existing devices, such as the heavy liquid bubble chamber and beams available at CERN, we use the numerical estimates of Table Ib to obtain a branching ratio of ~2% for the sum of the reactions $\bar{\nu}+n\to\Sigma^-+\mu^+$ and $\bar{\nu}+n\to Y_1{}^{*-}+\mu^+$, $Y_1{}^{*-}\to\Lambda^0+\pi^-$. We can now compare these rates with the corresponding $\Delta S=-\Delta Q$ reactions $\nu+n\to\Sigma^+ +\mu^-$, $\nu+n\to Y_1{}^{*+}+\mu^-$, $Y_1{}^{*+}\to\Lambda^0+\pi^+$. In about two months of running in a neutrino beam, the CERN freon bubble chamber[2] can collect ~800 interactions of all types. Using the 2% rate, we thus estimate about 16 events of $\Delta S=-\Delta Q$ if $x=1$. If none are observed, this would constitute a 6% upper limit.

Test of $\Delta I=1/2$ for $\Delta S=+\Delta Q$.—This selection law can also be tested in a model-independent way by noting that the ratio of the Reactions (9) and (8) in Table Ib, i.e., $\Gamma(\bar{\nu}+n\to\Sigma^-+\mu^+)/\Gamma(\bar{\nu}+p$

Table Ia. Predictions for neutrino reactions.

	Reaction	Unitary coupling	Structure of matrix element	Square of coupling coefficient	Estimated rates
(1)	$\nu+n\to p+\mu^-$	$8\otimes 8$	$\gamma_\mu+1.25\gamma_\mu\gamma_5$	$\cos^2\overline{\theta}$	47.0
(2)	$\nu+p\to N^{*++}+\mu^-$	$10\otimes 8$	$_\mu(\gamma_5-G_A\{10\}/G)$	$(12/5)\cos^2\overline{\theta}$	39.8
(3)	$\nu+n\to N^{*+}+\mu^-$	$10\otimes 8$	$_\mu(\gamma_5-G_A\{10\}/G)$	$(4/5)\cos^2\overline{\theta}$	13.2

Table Ib. Predictions for antineutrino reactions.

	Reaction	Unitary coupling	Structure of matrix element	Square of coupling coefficient	Estimated rates
(4)	$\overline{\nu}+p\to n+\mu^+$	$8\otimes 8$	$\gamma_\mu+1.25\gamma_\mu\gamma_5$	$\cos^2\overline{\theta}$	39.5
(5)	$\overline{\nu}+p\to N^{*0}+\mu^+$	$10\otimes 8$	$_\mu(\gamma_5-G_A\{10\}/G)$	$(4/5)\cos^2\overline{\theta}$	11.1
(6)	$\overline{\nu}+n\to N^{*-}+\mu^+$	$10\otimes 8$	$_\mu(\gamma_5-G_A\{10\}/G)$	$(12/5)\cos^2\overline{\theta}$	33.3
(7)	$\overline{\nu}+p\to\Lambda^0+\mu^+$	$8\otimes 8$	$\gamma_\mu+0.62\gamma_\mu\gamma_5$	$\frac{3}{2}\sin^2\overline{\theta}$	1.6
(8)	$\overline{\nu}+p\to\Sigma^0+\mu^+$	$8\otimes 8$	$\gamma_\mu-0.65\gamma_\mu\gamma_5$	$\frac{1}{2}\sin^2\overline{\theta}$	0.5
(9)	$\overline{\nu}+n\to\Sigma^-+\mu^+$	$8\otimes 8$	$\gamma_\mu-0.65\gamma_\mu\gamma_5$	$\sin^2\overline{\theta}$	1.0
(10)	$\overline{\nu}+p\to Y_1^{*0}+\mu^+$	$10\otimes 8$	$_\mu(\gamma_5-G_A\{10\}/G)$	$(2/5)\sin^2\overline{\theta}$	0.4
(11)	$\overline{\nu}+n\to Y_1^{*-}+\mu^+$	$10\otimes 8$	$_\mu(\gamma_5-G_A\{10\}/G)$	$(4/5)\sin^2\overline{\theta}$	0.8
(12)	$\overline{\nu}+p\to Y_0^{*0}+\mu^+$	$1\otimes 8$	$\gamma_\mu\gamma_5-G_A\{1\}/G\gamma_\mu$	$6\sin^2\overline{\theta}$	11.8

Table Ic. Predictions for leptonic decays of hyperons.

	Decay mode	Unitary coupling	Structure of matrix element	Square of coupling coefficient	Branching ratio
(13)	$\Omega^-\to\Xi^0+e^-+\overline{\nu}$	$10\otimes 8$	$_\mu(\gamma_5-G_A\{10\}/G)$	$(12/5)\sin^2\overline{\theta}$	
(14)	$\Xi^-\to\Lambda^0+e^-+\overline{\nu}$	$8\otimes 8$	$\gamma_\mu-0.02\gamma_\mu\gamma_5$	$\frac{3}{2}\sin^2\overline{\theta}$	0.35×10^{-3}
(15)	$\Xi^-\to\Sigma^0+e^-+\overline{\nu}$	$8\otimes 8$	$\gamma_\mu+1.25\gamma_\mu\gamma_5$	$\frac{1}{2}\sin^2\overline{\theta}$	0.07×10^{-3}
(16)	$\Xi^0\to\Sigma^++e^-+\overline{\nu}$	$8\otimes 8$	$\gamma_\mu+1.25\gamma_\mu\gamma_5$	$\sin^2\overline{\theta}$	0.26×10^{-3}

$\to\Sigma^0+\mu^+$) must be 2:1 if $\Delta I=1/2$. This is clear because we couple an $I=1$ (Σ) state to $I=1/2$ (N) to form the 1/2 state. The same argument predicts that the absolute decay rates for the cascade particles, $\Gamma(\Xi^0\to\Sigma^++e^-+\overline{\nu})/\Gamma(\Xi^-+\Sigma^0+e^-+\overline{\nu})=2:1$, as well as the ratio 2:1 for $\Gamma(\overline{\nu}+n\to Y_1^{*-}+\mu^+)/\Gamma(\overline{\nu}+p\to Y_1^{*0}+\mu^+)$.

Test of $\Delta I=1$ for $\Delta S=0$.—Reaction rates (2), (3) and (5), (6) of Tables Ia and Ib afford a model-independent test of $\Delta I=1$. Here, we combine $I=3/2$ (N^*) with $I=1/2$ (N) to make $I=1$. The predicted ratios are $\Gamma(\nu+p\to N^{*++}+\mu^-)/\Gamma(\nu+n\to N^{*+}+\mu^-)=\Gamma(\overline{\nu}+n\to N^{*-}+\mu^+)/\Gamma(\overline{\nu}+p\to N^{*0}+\mu^+)=3:1$.

Test of $\Delta S=2$.—This forbidden transition can readily be detected by the occurrence of the reactions

$$\nu+n\to\Xi^0+\mu^-,$$
$$\overline{\nu}+n\to\Xi^-+\mu^+,$$
$$\overline{\nu}+p\to\Xi^0+\mu^+.$$

We now make a model of the weak interactions in order to estimate experimental rates for various processes. The model uses current-current coupling, employing phenomenological direct four-fermion interactions which introduce baryon-antibaryon couplings of the type $\bar{N}N^*$, $\bar{N}Y_1^*$, and $\bar{N}Y_0^*$, as well as the more conventional $\bar{N}N$ and $\bar{N}Y$ types. Such a model introduces a structure into which all baryon states (excited, as well as ground states) enter symmetrically. We assume that the baryons have the unitary symmetry called the "eightfold way."[3] We follow Cabibbo[4] by introducing a baryon current of "unit length"[5] $J_\mu = \cos\theta J_\mu^{(0)} + \sin\theta J_\mu^{(1)}$, where $J_\mu^{(0)}$ represents the strangeness-nonchanging portion of the interaction and $J_\mu^{(1)}$ represents the strangeness-changing portion, J_μ is an irreducible tensor (with space-time properties of V,A) in SU(3) space which transforms according to the eightfold representation. Further, the vector part of J_μ is in the same octet as the electromagnetic current. We note that J_μ has matrix elements not only for transitions between the stable baryon octet of spin-parity $\frac{1}{2}^+$ $(n, p, 3\Sigma, \Lambda, 2\Xi)$ and itself, but also between the unitary decuplet of $\frac{3}{2}^+$ ($4N^*$, the $\frac{3}{2}$-$\frac{3}{2}$ π-p resonance; $3Y^*$, the 1385-MeV Λ-π resonance; $2\Xi^*$; Ω^-, the hypothesized $S=-3$ baryon state whose mass is expected to be ~1680 MeV) and the octet, as well as between the unitary singlet of $\frac{1}{2}^-$ (Y_0^*, the 1405-MeV Σ-π resonance) and the octet. We limit our considerations to transitions to the stable octet because these are our target materials in nature. Such a model automatically limits us to the selection rules $\Delta S = \Delta Q$, $\Delta I = \frac{1}{2}$ and $\Delta S = 0$, $\Delta I = 1$. Further, in the limit of zero momentum transfer, for $\Delta S = 0$ transitions of the type $n \to p$, since the vector portion of J_μ is in the electromagnetic octet, we have an exactly conserved vector current (ignoring electromagnetic interactions). However, for $\Delta S = \Delta Q$ transitions of the type $\Sigma^- \to n$, the conserved vector-current hypothesis is only correct if we also ignore the rather large SU(3)-violating interaction that we observe in nature.

From the above J_μ, we can form the octet-octet matrix elements

$$\langle \bar{A}\{8\} | J_\mu^{(j)} | B\{8\}\rangle = [f_{ABj} O_\mu\{8\} + d_{ABj} E_\mu\{8\}] \times \cos\theta_8 (\tan\theta_8)^j, \quad j = 0, 1, \tag{4a}$$

where the d's and f's play the role of unitary Clebsch-Gordon coefficients[6] corresponding to the two 8's occuring in $8 \otimes 8$, with the d and f corresponding to the even and odd representations, respectively. The O_μ and E_μ are[7] the reduced matrix elements $O_\mu = G_V\{8\}\gamma_\mu - G_A\{8\}\gamma_\mu\gamma_5$, and $E_\mu = G_V'\{8\}\gamma_\mu - G_A'\{8\}\gamma_\mu\gamma_5$. Similarly, the singlet-octet matrix elements are given by

$$\langle \bar{A}\{1\} | J_\mu^{(j)} | B\{8\}\rangle = O_\mu\{1\} \cos\theta_1 (\tan\theta_1)^j, \quad j = 0, 1, \tag{4b}$$

where $O_\mu\{1\} = G_V\{1\}\gamma_\mu\gamma_5 - G_A\{1\}\gamma_\mu$. The unitary coefficient is 1 because $1 \otimes 8 = 8$. We have assumed that A has $\frac{1}{2}^-$. Because of the parity flip with respect to the nucleon, the roles of γ_μ and $\gamma_\mu\gamma_5$ are interchanged. If the Y_0^* turns out to be $\frac{1}{2}^+$, we must interchange the above definitions of $G_V\{1\}$ and $G_A\{1\}$. Finally, the decuplet-octet elements are given by

$$\langle \bar{A}\{10\} | J_\mu^{(j)} | B\{8\}\rangle = e_{ABj} O_\mu\{10\} \cos\theta_{10} (\tan\theta_{10})^j, \quad j = 0, 1, \tag{4c}$$

where the e_{ABj} corresponds to the coefficient associated with the single 8 resulting from $10 \otimes 8$. The $O_\mu\{10\}$ is given by $_\mu(G_V\{10\}\gamma_5 - G_A\{10\})$, which is the abbreviation for $\langle \bar{A}_\mu\{10\} | G_V\{10\}\gamma_5 - G_A\{10\} | B\{8\}\rangle$. We have coupled the spin $\frac{3}{2}$ $(\bar{A}\{10\})$ with the $\frac{1}{2}$ $(B\{8\})$ to achieve spin 1 without introducing derivative coupling.[8] We note the vector portion of the current is associated with the term $G_V\{10\}\gamma_5$, and the axial vector with $G_A\{10\}$.

The strong interactions, in turn, will mix all of the representations, and will, for example, cause $\bar{N}N \to \bar{N}N^*$ transitions, as well as the reverse. Thus, it is reasonable to expect that the vector portions of all of the reduced matrix elements are of the same order of strength, i.e., $G_V\{1\} \approx G_V\{10\} \approx G_V\{8\} = G$, the universal Fermi constant. We call such a model a "unitary-universal" interaction. It should be noted that exact equality of the various G_V's would imply a restrictive condition on the strong interactions as well as the weak.

We adopt, for numerical computation, $G_V\{8\} = G_V\{1\} = G_V\{10\} = G$, and use Cabibbo's[4] results, $G_V'\{8\} = 0$, $G_A\{8\} = -0.30$ G, $G_A'\{8\} = -0.95$ G, with $\theta = 0.26$. Further, for purposes of numerical orientation, we set $G_A^2\{10\} = G_A^2\{1\} = G^2$. We note that the appropriate squared matrix element, summed over final spins and averaged over initial spins, is proportional to $G_V^2 + 3G_A^2$ for the $8 \otimes 8$ coupling, to $2G_A^2\{10\}$ for the $10 \otimes 8$ case, and to $3G_V^2 + G_A^2$ for the $1 \otimes 8$, if we take the static limit that the masses of all baryons are equal and that the reactions proceed with zero momentum transfer. We can now estimate that the leptonic decay $\Omega^- \to \Xi^0 + e^- + \bar{\nu}$ should have a decay rate ~10^8 sec^{-1}, corresponding to a branching ratio $\gtrsim 1\%$ for a lifetime $\gtrsim 10^{-10}$ sec. The numerical rates indicated in Tables Ia and Ib are crude estimates where effects of phase space, nucleon form factors, etc., are ignored and the rates are taken proportional to the squares of the indicated matrix elements in the static limit.

The power and new insight available from high-energy neutrino and antineutrino experiments is clear from an inspection of Tables I(a) and I(b). Whereas Reaction (7) could have its matrix element experimentally studied in the corresponding decay mode $\Lambda^0 \to p + \mu^- + \bar{\nu}$, the leptonic-decay analog has a vanishingly small branching ratio for Reaction (8). Thus, the neutrino processes allow us to examine the leptonic "decays" of Σ^0, N^*, Y_1^*, and Y_0^*, as well as the more conventional varieties such as n, Λ^0, and Σ^-. The estimated rates are all sufficiently large to be reasonably investigated in a large bubble chamber. We calculate approximately equal ratios of elastic (47 %) and inelastic (53 %) scattering in a high-energy neutrino experiment,[2] as shown in Table Ia, as well as a π^+/π^0 ratio of 5. For convenience, we have summarized the branching ratios for $8 \otimes 8$ coupling for leptonic hyperon decay[4] in Table Ic.

We can test predictions in the $10 \otimes 8$ coupling by noting that

$$\frac{\Gamma(\bar{\nu}+p \to Y_1^{*0}+\mu^+)+\Gamma(\bar{\nu}+n \to Y_1^{*-}+\mu^+)}{\Gamma(\bar{\nu}+p \to N^{*0}+\mu^+)+\Gamma(\bar{\nu}+n \to N^{*-}+\mu^+)} = \tfrac{3}{8}\tan^2\theta = 0.027,$$

if unitary coupling is correct. A measurement of N^* yield relative to elastic scattering will determine $G_A\{10\}$ and $G_V\{10\}$. Then, the branching ratio for the decay $\Omega^- \to \Xi^0 + e^- + \bar{\nu}$ can be used to check these parameters. A measurement of Y_0^* yield will fix the parameters $G_A\{1\}$ and $G_V\{1\}$. Further, we expect that the strange particles emitted will be longitudinally polarized. Thus, a measurement of the front-back asymmetry in Λ^0 decay in Reactions (7), (8), (10), (11), and in $\Sigma^+ \to p + \pi^0$ from (12) can independently provide tests of the coupling scheme.

In addition, we can explore the form factors for both the hyperons and the excited resonances, as well as the nucleon form factors, by detailed studies of the appropriate cross sections as a function of momentum transfer. The polarization analysis allows one to then separate the axial-vector structure from the vector structure. Parenthetically, we also note that by producing the strange isobars Y_1^* and Y_0^* using $\bar{\nu}$'s as a probe, we are able to observe their decays via the strong interactions without any interference phenomena from other strongly interacting particles, a situation not achievable by other means.

In summary, we see that neutrino experiments provide us with an elegant and powerful new probe to test the structure of both the weak interactions and the strong interactions.

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[7]The $O_\mu, E_\mu\{8\}$ are really abbreviations for the matrix elements $\langle \bar{A}\{8\}|G_V\{8\}\gamma_\mu - G_A\{8\}\gamma_\mu\gamma_5|B\{8\}\rangle$, etc., and similarly for $O_\mu\{1\}$.

[8]This is no longer possible using a spin-$\frac{5}{2}$ particle coupling to spin $\frac{1}{2}$. For this case, derivative coupling by necessity is introduced, which means that the matrix element will be proportional to the momentum transfer. Thus, at low momentum transfer, this matrix element will be severely depressed relative to the other terms considered above. For this reason, we have neglected other possible matrix elements, e.g., the possibility of J_μ coupling the second octet of baryons of spin $\frac{5}{2}$ (the octet containing the second π-p resonance) to the stable octet of spin $\frac{1}{2}$.