Markstein, and Yang,[4] and by others.[5] If η is indeed 1/4, as predicted by the Feinberg-Pais theory,[1] the cross section is increased by 33%; if η is instead 3/8,[6] the increase is 60%.

Since production by neutrinos is at present the most promising method of searching for the intermediate boson, we expect to gain some knowledge about the value of η as soon as the intermediate boson is found and its mass determined experimentally. It seems quite possible that the values of the production cross sections at several energies can be used to fix the three parameters m, η, and the magnetic moment.

I am greatly indebted to Professor C. N. Yang, Dr. Yih Pwu, and Professor A. Pais for very helpful discussions. I would also like to thank Professor J. R. Oppenheimer for his hospitality at the Institute for Advanced Study.

*Alfred P. Sloan Foundation Fellow. Permanent address: Harvard University, Cambridge, Massachusetts.

[1]G. Feinberg and A. Pais, Phys. Rev. 131, 2724 (1963).

[2]T. D. Lee and C. N. Yang, Phys. Rev. 128, 885 (1962); T. D. Lee, Phys. Rev. 128, 899 (1962).

[3]T. D. Lee and C. N. Yang, Phys. Rev. 119, 1410 (1960).

[4]T. D. Lee, P. Markstein, and C. N. Yang, Phys. Rev. Letters 7, 429 (1961).

[5]J. S. Bell and M. Veltman, Phys. Letters 5, 94 (1963); A. C. T. Wu and C. P. Yang (private communication).

NEW BARYON-LEPTON SYMMETRY PRINCIPLE FOR LEPTONIC WEAK INTERACTIONS*

R. E. Marshak and C. Ryan†
Department of Physics and Astronomy, University of Rochester, Rochester, New York

and

T. K. Radha‡ and K. Raman
Institute of Mathematical Sciences, Madras, India
(Received 3 September 1963)

Baryon-lepton symmetry[1] was first defined as invariance of the four-fermion weak interaction Lagrangian under the simultaneous transformation $\Lambda \to \mu^-$, $n \to e^-$, $p \to \nu$. This symmetry principle assumed one neutrino and the Sakata[2] (triplet) model of strong interactions. The existence of two distinct neutrinos[3] and the superiority of the octet model[4] of strong interactions over the Sakata model has led us to a new scheme of baryon-lepton symmetry for leptonic weak interactions which is consistent with the latest experiments and which makes some well-defined predictions that can be tested by further experiment.

We set up the correspondence between the baryon octet and the octet of leptons and antileptons[5] given in Table I. In writing down Table I, we accept two neutrinos but postulate that the electron neutrino is described by a Dirac four-component[6] spinor $\nu_e(x)$, while the muon neutrino is described by a Majorana field[7] $\chi(x) = [\nu_\mu(x) + \nu_\mu^C(x)]/$

Table I. Baryon-lepton correspondence.

Quantum number and particle correspondence					Field operator correspondence		
Baryon	Lepton	(L)	I	$-X$	Lepton field		Baryon field
p	e^+	(-1)	$\frac{1}{2}$	1	$e^C(x)$	$\longleftrightarrow$	$-\sqrt{2}p(x)$
n	$\bar{\nu}_e$	(-1)	$\frac{1}{2}$	1	$\nu_e^C(x)$	$\longleftrightarrow$	$\sqrt{2}n(x)$
Λ	$\psi = (\nu_\mu - \nu_\mu^C)/\sqrt{2}$	(1)	0	0	$\psi(x)$	$\longleftrightarrow$	$\sqrt{2}\Lambda(x)$
Σ^+	μ^+	(1)	1	0	$\mu^C(x)$	$\longleftrightarrow$	$\sqrt{2}\Sigma^+(x)$
Σ^0	$\chi = (\nu_\mu + \nu_\mu^C)/\sqrt{2}$	(-1)	1	0	$\chi(x)$	$\longleftrightarrow$	$2\Sigma^0(x)$
Σ^-	μ^-	(-1)	1	0	$\mu(x)$	$\longleftrightarrow$	$\sqrt{2}\Sigma^-(x)$
Ξ^0	ν_e	(1)	$\frac{1}{2}$	-1	$\nu_e(x)$	$\longleftrightarrow$	$\sqrt{2}\Xi^0(x)$
Ξ^-	e^-	(1)	$\frac{1}{2}$	-1	$e(x)$	$\longleftrightarrow$	$\sqrt{2}\Xi^-(x)$

$\sqrt{2}$ (ν_μ is a four-component Dirac spinor). Further, we have matched up leptons and baryons of the same charge and then assigned the "weak" hypercharge X to each lepton so that it is equal to the strong hypercharge Y of its baryonic counterpart. The lepton number L (placed in parentheses besides each lepton in Table I) corresponds to the invariance of the theory under the simultaneous transformation[8]

$$e(x)\to e^{i\alpha}e(x),\quad \nu_e(x)\to e^{i\alpha}\nu_e(x),$$
$$\mu(x)\to e^{-i\alpha}\mu(x),\quad \chi(x)\to e^{-i\alpha\gamma_5}\chi(x),$$
$$\psi(x)\to e^{i\alpha\gamma_5}\psi(x).$$

We notice that baryon-lepton symmetry is preserved under the operation of R conjugation[9] on the baryons accompanied by particle-antiparticle conjugation on the leptons. In addition, we may think of (e^-, ν_e) and $(\bar{\nu}_e, e^+)$ as isodoublets ($I=\frac{1}{2}$), (μ^+, χ, μ^-) an an isotriplet ($I=1$), and ψ as an isosinglet ($I=0$), and we have the charge relation $Q = I_3 + \frac{1}{2}X$. The inclusion of both particles and their antiparticles in the lepton octet need cause no concern because this is also done in the boson octet and, further, the relative odd parity of leptons and antileptons is irrelevant since parity is not conserved in weak interactions.

The weak interaction Lagrangian $\mathcal{L}_{\rm int}$ is now supposed to consist of two parts, the first corresponding to strangeness-conserving and the second to strangeness-violating processes. Each part consists of a self-coupling of a charged current,[10] so that

$$\mathcal{L}_{\rm int} = (G_0/\sqrt{2})J_0J_0^+ + (G_1/\sqrt{2})J_1J_1^+, \qquad (1)$$

where the subscripts on the J's denote the changes in ΔX (see below). In order to determine the explicit form of $\mathcal{L}_{\rm int}$, we impose the following requirements:

(a) Each current consists of a sum of chiral invariant[11] lepton and baryon terms in such a way that it is invariant under the field operator interchange of Table I.

(b) L, B, and X are separately conserved by each term of $\mathcal{L}_{\rm int}$. As an immediate conclusion from (a) and (b), J_0 and J_1 must be $\Delta L = 0$ currents and this has the important consequence that only $\Delta Q/\Delta X = 1$ strangeness-changing currents are allowed. To see this, note that the only $\Delta Q = -1$, $\Delta L = 0$ chiral invariant terms with $\Delta X = 0$ which can be constructed on the basis of Table I are $(\bar{e}O_-X)$, $(\bar{e}O_+\psi)$, $(\bar{\mu}O_\pm\nu_e^{\,c})$ $[O_\pm = \gamma_\lambda(1\pm\gamma_5)]$, and each of these has $\Delta X = -1$. Thus $\Delta Q/\Delta S = -1$ reactions are automatically excluded (since, for baryon currents, $\Delta X = \Delta Y = \Delta S$).

The currents J_0 and J_1 can now be written down explicitly, namely,

$$J_0 = \{\tfrac{1}{2}[(\bar{e}O_+\nu_e) - (\bar{\nu}_e^{\,c}O_-e^c) + (\bar{\mu}O_+\chi) - (\bar{\chi}O_-\mu^c)]$$
$$+[(\bar{\Xi}^-O_+\Xi^0) + (\bar{n}O_-p)$$
$$+\sqrt{2}(\bar{\Sigma}^-O_+\Sigma^0 - \bar{\Sigma}^0O_-\Sigma^+)]\}. \qquad (2)$$

We see that the baryon terms in (2) are just those required by the conserved vector current (CVC) hypothesis; the use of the Majorana field χ is essential in this connection. One notes also that the vector part of the lepton current in (2) can be regarded as the $(I_1 - iI_2)$ component of an isovector as in the case of the baryon current.[12] For the strangeness-changing current, if we assume that ψ is not coupled at all,[13] we obtain

$$J_1 = \{\tfrac{1}{2}[(\bar{e}O_-\chi) - (\bar{\chi}O_+e^c) + (\bar{\mu}O_+\nu_e^{\,c}) - (\bar{\nu}_eO_-\mu^c)]$$
$$+[\sqrt{2}(\bar{\Xi}^-O_-\Sigma^0) + \sqrt{2}(\bar{\Sigma}^0O_+p)$$
$$+(\bar{\Sigma}^-O_+n) - (\bar{\Xi}^0O_-\Sigma^+)]\}. \qquad (3)$$

As expected from our previous discussion, this is a pure $\Delta Q/\Delta S = 1$ current and, moreover, the baryonic part is a linear combination[14] of $I=\frac{1}{2}$ and $I=\frac{3}{2}$ currents. Conservation of L and the experimental evidence[15] that the muon in $K_{\mu 2}$ decay is left-handed fixes the muon term in J_1 as $(\bar{\mu}O_+\nu_e^{\,c})$ (and by the same token excludes a Majorana electron neutrino).

We give now some of the more striking consequences of (2) and (3). In the first place, the purely leptonic process $\mu\to e+\nu_e+\chi$ receives (incoherent) contributions from both J_0 and J_1; the distribution in energy and angle (relative to muon polarization) is given by

$$dN(x,\cos\theta) = \frac{G_0^{\,2}m_\mu^{\,5}x^2}{32\pi^3}\{[(\tfrac{1}{2}-\tfrac{1}{3}x) + f^2(1-x)]$$
$$\pm\tfrac{1}{3}\cos\theta[(\tfrac{1}{2}-x) + 3f^2(1-x)]\}dx\,d(-\cos\theta). \qquad (4)$$

In (4), the electron mass is neglected; $x = E_e/(E_e)_{\rm max}$, E_e and $(E_e)_{\rm max}$ being the electron energy and the maximum electron energy, $f=(G_1/G_0)$, and the + and - signs refer to μ^- and μ^+ decays, respectively. The total decay rate is

$$\Gamma=(G_0{}^2/6\pi^3)(\tfrac{1}{2}m_\mu)^5(1+f^2).$$

For comparison, we remark that the conventional theory follows from (4) by setting $f=0$. Thus, the present theory predicts slight deviations from the conventional theory for the angular distribution, particularly at low electron energies, while the f^2 term in the decay rate offers a possible explanation of the slight discrepancy which may exist in relating (through CVC) the muon decay rate and the vector-coupling constant in β decay.[16]

As regards the $\Delta S=0$ decays of strongly interacting particles, we note that we no longer have a universal $(V\text{-}A)$ theory since the "bare" Lagrangian (1) contains O_- as well as O_+ [Eqs. (2) and (3)]. In fact, the "bare" β-decay and μ-capture interactions are now $(V+A)$ which implies that strong renormalization effects must convert the "bare" $(V+A)$ into the observed $(V-1.2A)$ structure for nuclear β decay.[17]

With regard to the strangeness-changing decays, they have the common features of neutrino flip and $\Delta Q/\Delta S=1$. Neutrino flip in the present theory is similar to that in previous theories,[18] except that we avoid the previous difficulties. Before, the neutrino from $K_{\mu 2}$ decay, upon interacting with a nucleon, could produce an electron according to the chain

$$K^-\to\mu^-+\bar{\nu}_e;\quad \bar{\nu}_e+p\to n+e^+$$

in apparent contradiction with experiment.[3] In the present formulation, this type of chain is excluded by the structure of J_0 and J_1 [note that the four-component ν_e is coupled differently in (2) and (3)]. On the other hand, neutrino flip can be detected through hyperon production processes via such chains as

$$\pi^+\to\mu^++\chi;\qquad \left.\begin{array}{l}\chi+p\to\Sigma^0(\Lambda)+e^+\\ \chi+n\to\Sigma^-+e^+\end{array}\right\}, \tag{5a}$$

$$K^-\to\mu^-+\nu_e;\quad \left.\begin{array}{l}\nu_e+p\to\Sigma^0(\Lambda)+\mu^+\\ \nu_e+n\to\Sigma^-+\mu^+\end{array}\right\}. \tag{5b}$$

Processes (5a) and (5b) are not in contradiction with experiment[3] because of the anticipated reduction in cross section by a factor of 20, at least at small momentum transfers (see below). It should be noted that if X is an additive quantum number, as we have assumed so far, neutrino flip is prohibited, even with hyperon production, for the neutrinos from the decays $\pi^-\to\mu^-+\chi$ and $K^+\to\mu^++\bar{\nu}_e$ [χ is now right-handed—instead of left-handed as in (5a)—and $\bar{\nu}_e$ has the opposite sign of X compared to that of ν_e in (5b)].

The experimental situation with regard to $\Delta Q/\Delta S=-1$ decays is more confusing at present. The evidence from the leptonic decays of $K_1{}^0$ and $K_2{}^0$ would indicate a substantial admixture of $\Delta Q/\Delta S=-1$ in the strangeness-changing current,[19] but the rarity[20] of the $\Sigma^+\to n+\mu^++\nu$ decay relative to $\Sigma^-\to n+\mu^-+\nu$ is not consistent with the neutral kaon evidence. Furthermore, the recent experiment[21] on K_{e4} favors a preponderance of $\Delta Q/\Delta S=1$. From our point of view, deviations from the $\Delta Q/\Delta S=1$ rule would be ascribed to a "broken symmetry."

We have not said anything so far about the coupling constants G_0 and G_1. G_0 is, of course, the vector coupling constant for nuclear β decay, and the fact that the strangeness-violating leptonic decays of the baryons all take place at a rate about 20 times slower than strangeness-conserving decays[20] indicates that the "bare" G_1 is probably smaller than the "bare" G_0, say $G_1/G_0\simeq\frac{1}{4}$. A rather attractive mechanism to explain this common diminution of effective interaction strengths and, at the same time, to achieve universality of the theory is to introduce two kinds of intermediate charged vector bosons[22]: $W_0{}^\pm$ with $L=B=X=0$ and $W_1{}^\pm$ with $L=B=0$, $X=\pm1$. Our weak-interaction Lagrangian would then become

$$\mathcal{L}_{\text{int}}=igW_0J_0+igW_1J_1, \tag{7}$$

where J_0 and J_1 are the same currents as before, g is a universal dimensionless "semiweak" coupling constant, and B, L, Q, and X are all conserved. The constants G_0 and G_1 in (1) are related to g by

$$G_0/\sqrt{2}=g^2/M_0{}^2,\quad G_1/\sqrt{2}=g^2/M_1{}^2. \tag{8}$$

If we choose $M_1\simeq 2M_0$, we obtain the required diminution $G_1/G_0\simeq\frac{1}{4}$. The intermediate bosons W_0 and W_1 provide a natural basis for the restriction to the charged currents J_0 and J_1 and the noninterference of these two currents in the effective interaction. The noninterference of J_0 and J_1 precludes a "current-current" explanation of nonleptonic weak processes.[23]

The essential consequences of our theory do not depend upon the existence of the intermediate bosons W_0 and W_1 but, if they do exist, their different decay modes can be predicted on the basis of their quantum number assignments and the conservation laws which we have employed. These and other details we be presented in a separate paper.

The authors wish to thank Dr. I. B. Birula, Dr. S. Okubo, and Dr. E. C. G. Sudarshan for stimulating discussions. This work was started in February 1963 while one of the authors (R.E.M.) was a Niels Bohr visiting professor at the Institute for Mathematical Sciences, Madras, India. He is grateful to the director of this institute, Professor A. Ramakrishnan, for the hospitality which he enjoyed.

---

*This work was supported in part by the U. S. Atomic Energy Commission.

†On leave from the Institute for Advanced Studies, Dublin, Ireland.

‡Now on leave at Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California.

[1]A. Gamba, R. E. Marshak, and S. Okubo, Proc. Natl. Acad. Sci. U.S. 45, 881 (1959).

[2]S. Sakata, Progr. Theoret. Phys. (Kyoto) 16, 686 (1956).

[3]G. Danby et al., Phys. Rev. Letters 9, 26 (1962); 10, 260 (1963).

[4]The spin $\frac{1}{2}$ of Ξ is an argument against the Sakata model [M. Ikeda, S. Ogawa, and Y. Ohnuki, Progr. Theoret. Phys. (Kyoto) 22, 715 (1959)], whereas the fulfillment of the mass relations is evidence for the octet model [see Y. Nee'man, Nucl. Phys. 26, 222 (1961); M. Gell-Mann, Phys. Rev. 125, 1067 (1962); S. Okubo, Progr. Theoret. Phys. (Kyoto) 27, 969 (1962)]. It will become evident that we do not use the octet model in the full sense of the SU_3 group.

[5]Various proposals have been made for a new baryon-lepton principle based on the octet model, but they have all been of rather limited scope {see S. Oiglane, Zh. Eksperim. i Teor. Fiz. 40, 782 (1961) [translation: Soviet Phys.–JETP 13, 548 (1961)]; J. M. Cornwall and V. Singh, Phys. Rev. Letters 10, 551 (1963)}.

[6]The four-component spinor character of ν_e may be important for explaining the $(e - \nu_e)$ mass difference as an electromagnetic effect [see R. E. Marshak and S. Okubo, Nuovo Cimento 19, 1226 (1961); K. Johnson and M. Baker, Proceedings of the Rochester Seminar on Unified Theories of Elementary Particles, July 1963]. A four-component Dirac neutrino is equivalent, of course, to two two-component (Weyl) neutrinos.

[7]The distinction between the electron and muon neutrinos (as well as the mass difference between e and μ due to the electromagnetic interaction) may lie precisely in the different properties of Dirac and Majorana massless fields. A four-component Majorana neutrino is equivalent to one two-component neutrino (see reference 8).

[8]For a complete discussion of the use of Majorana fields to describe neutrinos, see C. Ryan and S. Okubo (to be published).

[9]See S. Okubo and R. E. Marshak, Nuovo Cimento 28, 56 (1963).

[10]We have no evidence for neutral lepton currents and therefore, by baryon-lepton symmetry, neutral baryon currents must be omitted.

[11]E. C. G. Sudarshan and R. E. Marshak, Phys. Rev. 109, 1860 (1958).

[12]This is the only property required to explain the "weak-magnetism" experiment [Y. K. Lee, L. W. Mo, and C. S. Wu, Phys. Rev. Letters 10, 253 (1963)]. Of course, this statement implies that the mass differences within the isotopic multiplet may be neglected.

[13]This term would introduce a second muon neutrino which seems unnecessary at this stage; we are dealing with a septet model! This septet model was forced upon us for J_0 by CVC.

[14]It is possible to obtain a pure $I=\frac{1}{2}$ current by interchanging the coefficients 2 and $\sqrt{2}$ for the Σ triplet (see the last column of Table I), but the choice in Table I seems more natural.

[15]C. Coombes, B. Cork, W. Galbraith, G. Lambertson, and W. Wenzel, Phys. Rev. 108, 1348 (1957).

[16]See S. Berman and A. Sirlin, Ann. Phys. (N.Y.) 20, 20 (1962).

[17]This possibility is still an open question; a model which achieves this inversion of sign has been given by A. P. Balachandran, Nuovo Cimento 23, 1168 (1962).

[18]See G. Feinberg, F. Gürsey, and A. Pais, Phys. Rev. Letters 7, 208 (1961).

[19]R. P. Ely et al., Phys. Rev. Letters 8, 132 (1962); G. Alexander, S. Almeida, and F. Crawford, Phys. Rev. Letters 9, 69 (1962).

[20]W. J. Willis (private communication).

[21]R. W. Birge et al., Phys. Rev. Letters 11, 35 (1963).

[22]Various authors have postulated intermediate bosons with distinct properties but within different contexts [see S. Bludman, Phys. Rev. 124, 947 (1961); S. Nakamura and S. Sato, Progr. Theoret. Phys. (Kyoto) 29, 325 (1963)].

[23]The "current-current" approach to nonleptonic weak processes has been quite unsuccessful thus far, and these processes may have a completely different origin [see A. Salam and J. C. Ward, Phys. Rev. Letters 5, 390 (1960); S. Okubo and R. E. Marshak, Nuovo Cimento 20, 791 (1961)].