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P 8 Weak Interactions

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§1. Introduction

I will first offer a very brief review of the charged and neutral current weak interactions, and will then turn to some special topics in weak interaction physics.

§11. Charged Currents

We heard a review yeasterday by Tittel[1] of the experimental information on the high energy charged-current weak interactions of neutrinos. In brief, everything here is in agreement with expectations based on the parton model and the simple gauge theory.[2]

First, there is no more "high-j anomaly." That is not to say that quantities like *B*= *\xF₃dx/\F₂dx* and <y) are strictly constant, but rather, that there is no evidence for an energy dependence which would not be accounted for by the corrections to scaling predicted by QCD. (I believe that this is a matter on which all groups are now in substantial agreement.) Thus there is no evidence now for a right-handed coupling of the *u* or *d* quarks to other quarks, and in fact one can use this data to put an upper limit on the strength of any such coupling. Barnett[3] finds in this way that any coupling *g%(u₉ b)* of the right-handed *u* and *b* quarks must be less than a tenth of the usual coupling *g\(u, d).*

In addition, the total cross sections are behaving as they should. They are linear in neutrino lab energy, up to the highest energies studied (~250 GeV). According to an analysis[4] by the CalTech-Fermilab group, this implies a *W* mass greater than about 30 GeV.

Trimuons were also reviewed by Tittel.[1] These *itpN-*/*"/*"i^X* events are now essentially all explained by "conventional" mechanisms, including inner bremsstrahlung of *pt⁺iu~* pairs or associated *D⁺D~* production in *v^N-^prX* reactions.[5]

Even though the word "nuclear" is no longer in the title of these Conferences, I thought that I would also say a bit about classic weak interaction phenomena—that is, beta decay and allied low-energy charged current processes. Almost eveything that we know about beta decay and allied charged-current processes is incorporated in an effective current-current Hamiltonian

$$\mathscr{H}_{\rm eff}=\frac{1}{\sqrt{2}}G_F J_\lambda J^{\lambda+} \qquad \text{(i)}$$

in which the current is the sum of leptonic and *A S=0,* 1 vector and axial-vector hadronic currents

$$\begin{aligned}J_\lambda=\bar{e}\gamma_\lambda(1+\gamma_5)\nu_e+\bar{\mu}\gamma_\lambda(1+\gamma_5)\nu_\mu\\ +\cos\theta_c[V_\lambda^{\Delta s=0}+A_\lambda^{\Delta s=0}]\\ +\sin\theta_c[V_\lambda^{\Delta s=1}+A_\lambda^{\Delta s=1}].\end{aligned} \qquad (2)$$

The hadronic currents are supposed to satisfy the chiral SU(3) x SU(3) commutation relations of Gell-Mann; among other things, this fixes the normalization of the currents, and thus allows us to give a precise meaning to the Cabibbo angle *6꜀*. In addition, the currents are supposed to satisfy CVC and PCAC; that is, they are all approximately conserved (nearly exactly for *JS=0;* rather poorly for J.S=1), with the *rc* and *K* serving as Goldstone bosons for the spontaneously broken symmetry associated with *Af⁼⁰* and *Af⁼¹*. Finally, the *JS=0* currents are supposed to be of first class with respect to their G-transformation properties

$$GV_\lambda^{\Delta s=0}G^{-1}=+V_\lambda^{\Delta s=0} \quad GA_\lambda^{\Delta s=0}G^{-1}=-A_\lambda^{\Delta s=0}. \qquad (3)$$

This whole body of classic weak interaction theory is a mathematical consequence of QCD plus the simple gauge theory of weak and elctromagnetic interactions. In this framework, the gauge symmetry dictates that the *W~* couples to the currents *elₓ* (1 + f s K *>ftr z 0-+T&)v v>* and *(d*cos *d꜀-\-~s* sin *d꜀)jₓ{* +rsK just as gauge invariance in QED tells us that *Aₓ* couples to *eyₓe*. The properties of these currents can then be worked out by direct calculation, and one finds that they must satisfy all the established conservation, commutation, and *G*-conjugation rules. Thus, there continue to be deep connections between the classic part of weak interaction theory and high energy physics.

One aspect of classic weak interaction theory that has been studied experimentally in the last few years is the G-conjugation property of the axial-vector current. First-class terms in *Aj*$^{s=0}$ give nucleon matrix elements proportional to $y_h y\backslash$ or $y_h q_x$ (where $q=k_v—k_n$) while any second-class terms would give a matrix element of the induced-pseudotensor form $iy_5(J_{xv}g^v$. The conclusion reached on the basis of this experimental study is that there is no evidence for second-class currents, and good evidence that any second-class terms in the axial current must be quite small.[6] As a spin-off to this work, additional confirmation has also been found that "weak magnetism" has the value predicted by CVC.[7]

The absence of an induced pseudotensor term *j^^q^* in the nucleonic matrix element of the axial-vector current is a nice counterpart to the very well known absence of an intrinsic Pauli moment term $o_{Xv}q^v$ in the leptonic matrix element of the electromagnetic current, which would destroy the agreement between theory and experiment for *g-2* values in quantum electrodynamics. In both cases these terms would be allowed by current conservation, but are ruled out by the constraint of renormalizability, at least (for second-class currents) in the absence of strongly interacting scalar fields. The same reasoning also rules out any Konopinski-Uhlenbeck derivative coupling terms in the leptonic part of the weak current.

The current-current Hamiltonian (1) contains specific non-leptonic terms, but the difficulty of calculating effects of strong interactions at low energy has so far precluded quantitative calculations of non-leptonic weak processes. In particular, the *AI=\/2* rule is not yet satisfactorily understood. Attention has recently focussed[8] on a previously neglected term of the form $(sy_x T_a d) d_v F i^v$ in the operator product expansion of two charged currents. (Here Fi^v is the Yang-Mills curl of the gluon field, and r_a is the color SU(3) generator.) This is a pure *A1=1/2* term, but it remains to be seen whether its matrix elements are sufficiently enhanced to account for the *JI=l/2* rule.

§HL Neutral Currents

Baltay[9] gave a comprehensive summary here of the experimental data on neutral currents, and its comparison with the gauge theory. There is not much that I need to add, and I will only make some disconnected remarks.

Our most detailed experimental information on neutral current weak interactions comes from data on vN and vN reactions, including inclusive reactions *vN-+vX*, *\>N-+vX*, *vp-+vX*, *vp->vX* elastic scattering *vp-*vp*, *vp-*vp* semi-inclusive reactions *vN->vnX*, *VN-^VTZX*, and exclusive reactions *vN->vNn*, *VN-^VNTI:*. It has been clear for more than a year now that the empirical cross sections for these reactions are in good agreement with the predictions of the simple gauge theory, and recent data has further improved the precision of the agreement here between theory and experiment.[10]

The data on neutrino-electron reactions is less precise than for neutrino-nucleon reactions, because at any given lab energy above a few GeV, the cross sections are smaller by a factor m_e/m_N. Within the experimental uncertainties, data on $v_e e$, v^e, and *v^e* scattering has for some time all been in agreement with the simple gauge theory. This spring, the Gargamelle group for a while observed an unexpectedly large rate of *v^e* events, but some of these events have been withdrawn; the large event rate did not appear in analyses of further samples of Gargamelle data; and a much larger data sample of the Columbia-BNL group gave a *v^e~* cross section in good agreement with the simple gauge theory. As indicated here by Baltay,[9] an average of all data on v^e" scattering, including that from Gargamelle, gives a cross section of (1.7± 0.5) x1O^{-42} £$_v$cm^2/GeV, in excellent agreement with the gauge theory prediction of 1.5x1O^{-42}£$_y$cm^2/GeV.

The electron-nucleon neutral currents have been difficult to study experimentally, because electrons interact with nucleons electromagnetically, so that one must look for effects that are characteristic of the weak interactions, and in particular, for a parity violation. The first round of experiments on bismuth at Oxford and Seattle set upper limits on the optical rotation that were well below the level expected on the basis of the original atomic calculations using the simple gauge theory. However, subsequent atomic calculations revealed significant shielding corrections, leading to a large reduction in the theoretically expected circular polarization. Then the experimental situation itself became unclear, when the Novosibirsk group reported a circular polarization in bismuth in disagreement with the limit set at Oxford for the same frequency, but in agreement with the theoretical results as calculated by Novikov *et ah* in the gauge theory. At this Conference, we have heard an indirect report from the Riga Conference that the Oxford group are now observing a parity violation of the expected sign, and some three standard deviations above zero, but still in disagreement with that seen at Novosibirsk.[11]

On the basis of this experience, even if one did not know of the specific gauge theory predictions, one could only conclude that experiments on heavy atoms like bismuth may be a good way to learn about heavy atoms, but they are not a good way to learn about neutral currents. The conflict between the experimental values of the circular polarization reported from Oxford and Novosibirsk shows that these are hard experiments, subject to systematic errors that are difficult to eliminate. And even if the experimental conflict is resolved, there is still the formidable difficulty of calculating the circular polarization to be expected in a complicated atom like bismuth, for which theoretical results have already changed by more than a factor of two.[12] Fortunately, this is a problem that may now be left to the atomic physicists to settle at their leisure, because a far cleaner way has been found to determine the electron-nucleon neutral current interaction, in high energy collisions of polarized electrons with nucleons.

The deep inelastic cross sections for *eN-^eX* with left-or right-handed electrons striking an isoscalar target differ by a fractional amount, given in the simple gauge theory as[33]

$$A\equiv\frac{\sigma_R-\sigma_L}{\sigma_R+\sigma_L}=-\frac{9G_Fq^2}{20\sqrt{2}\,\pi\alpha}\times\left[1-\frac{20}{9}\sin^2\theta+(1-4\sin^2)\left(\frac{1-(1-y)^2}{1+(1-y)^2}\right)\right] \tag{4}$$

This asymmetry has now been measured in deuterium by a SLAC-Yale experiment, described here by Taylor.[13] At j=0.21, they find ^2=(-9.5±1.6)xl0-5GeV"2. This result puts it beyond doubt that parity is violated in the neutral currents, and is quantitatively in good agreement with the simple gauge theory prediction (4), which, for values of sin²/? in the range 0.20 to 0.25 indicated by *vN* and vTV data, yields a theoretical value for *A/q²* in the range (-9.7 to -7.2) X 10"5 GeV~² at j=0.21. A parity violation was also found in hydrogen, with a value also in agreement with theoretical expectations, but with a larger experimental uncertainty.

Apart from the gauge theory itself, the only theoretical input needed in deriving eq. (4) is the use of the parton model. Experience with deep inelastic electron and neutrino scattering at similar values of q^2 and y suggests that the parton model should work well here. Nevertheless, it is of interest to judge theoretically how much of the parton model is actually needed here. This has been clarified by a recent analysis by Wolfenstein.[14]

First, note that the asymmetry consists of two terms A_{AV} and A_{VA}, with A_{AV} arising from the product of the axial-vector electron current and the vector nucleon current, and A_{VA} from the product of the vector electron current and the axial vector nucleon current. In the parton model, the term in (4) proportional to 1—(20/9) sin²# gives A_{VA}, and the remaining term proportional to 1— 4sin²# gives A_{VA}. Now, without using the parton model, we know that A_{VA} vanishes at *y=0,* and vanishes for all *y* in the simple gauge theory if sin² *6*= 1/4. As it happens, the SLAC-Yale experiment was carried out at a low value of *y*, *y*= 0.21, and we know that sin² *d* is rather close to 1/4, so in the simple gauge theory A_{VA} is expected to make a relatively small contribution to *A.* (In the parton model, at *y=0.2l* and sin² #=0.20, the A_{VA} term in eq. (4) contributes only 8% of the total asymmetry.) Thus, it would not matter if the use of the parton model did introduce rather large errors in A_{VA}; the error introduced in *A* would still be small.

The AV term in $\sigma_R-\sigma_L$ involves an interference of the electromagnetic $J_e \cdot J_N$ interaction with the $A_e \cdot V_N$ weak neutral current interaction. The electromagnetic and weak neutral hadronic vector currents of the simple gauge theory are

$$J_\mu^{em}=\sum_n q_n\bar{Q}_n\gamma_\mu Q_n$$

$$V_\mu^{WK}=\sum_n q_n^Z\bar{Q}_n\gamma_\mu Q_n$$

with sums running over quark flavors, and

$$q_u=2/3,\quad q_s=q_d=-1/3$$

$$q_u^Z=1/2-4/3\sin^2\theta,\quad q_s^Z=q_d^Z=-1/2+2/3\sin^2\theta.$$

The AV term in $\sigma_R-\sigma_L$ then takes the form

$$(\sigma_R-\sigma_L)_{AV}=-(2G_F/\sqrt{2})(e^2/q^2)\sum_{nm} q_n q_m^Z F_{nm}$$

where F_{nm} is a structure function appearing in the Fourier transform of the target expectation value of the product of the vector currents of the nth, and mth quarks. The same structure functions appear in the total eN cross section

$$\sigma_R+\sigma_L=(e^2/q^2)^2\sum_{nm} q_n q_m F_{nm}.$$

The parton model would give $F_{nm}=0$ for $n\neq m$, because the collision of electrons with different quarks is supposed to lead to orthogonal final states. Of course, this is just an approximation, because recoiling quarks of different type *can* assemble themselves into the same final states, but it is a reasonable conclusion to abstract from any sort of parton model. In addition, the parton model suggests that for nuclear targets, we may neglect F_{ss}. With these two assumptions, the AV part of the asymmetry is

$$A_{AV}=A_0\left[\frac{q_u q_u^Z F_{uu}+q_d q_d^Z F_{dd}}{q_u^2 F_{uu}+q_d^2 F_{dd}}\right]$$

$$-A_0\equiv 2G_F q^2/(\sqrt{2}\,e^2)=G_F q^2/(2\sqrt{2}\,\pi\alpha). \tag{5}$$

For scattering on an isoscalar target $F_{uu}=F_{dd}$, so without further use of the parton model Wolfenstein finds

$$A_{AV}^{(d)}=A_0\left[\frac{q_u q_u^Z+q_d q_d^Z}{q_u^2+q_d^2}\right]=A_0\left[\frac{9}{10}-2\sin^2\theta\right] \tag{6}$$

in agreement with eq. (4). On the other hand, for a proton target we need to use the parton model to estimate $F_{uu}\simeq 2F_{dd}$; Equation (5) gives in this case

$$A_{AV}^{(p)}=A_0\left[\frac{2q_u q_u^Z+q_d q_d^Z}{2q_u^2+q_d^2}\right]=A_0\left[\frac{5}{6}-2\sin^2\theta\right]. \tag{7}$$

Finally, the neutral currents also contribute to a parity violation in the nucleon-nucleon interaction.[15] Unfortunately, even apart from the problems of dealing with complex nuclei, the difficulty of calculating soft gluon effects makes it impossible to predict the parity violation in NN or nN interactions that should be expected in the gauge theory.[16]

In all of the large number of cases where a comparison can reliably be made between theory and experimental data on charged and neutral current weak interactions, the results are found to confirm the simple gauge theory. It has been clear at this Conference that the simple gauge theory is in fact the correct theory of these interactions. In what follows, this theory will be used as a basis for the discussion of some topics of current interest in the physics of weak interactions.

§IV. New Leptons and Quarks

This section will deal with the weak interactions of the newest particles: the τ lepton, b quark, and further leptons and quarks.

1. τ Lepton[19]

The simplest assumption is that the τ lepton is a "sequential" lepton; that is, that e^-, μ^-, and τ^- are in three left-handed $SU(2)\times U(1)$ doublets

$$\begin{bmatrix}\nu_e'\\ e^-\end{bmatrix}_L \quad \begin{bmatrix}\nu_\mu'\\ \mu^-\end{bmatrix}_L \quad \begin{bmatrix}\nu_\tau'\\ \tau^-\end{bmatrix}_L \tag{8}$$

The primes indicate that if neutrinos have masses, then the ν' are in general linear combinations of particles of definite mass. It has been pointed out[17] that the existence of a third neutrino is strongly indicated by the non-observation of the neutral-current processes $\tau\to eee$, $ee\mu$, $e\mu\mu$, or $\mu\mu\mu$. [If there were no τ neutrino, then e^-, μ^-, and τ^- would have to be in doublets with linear combinations of ν_e and ν_μ, and mixing effects would give a total branching ratio for $\tau\to eee$, etc. of at least 5%, in contrast with an experimental upper limit of 1/2%.)

If the neutrinos are all massless, then the numbers of e, μ, and τ-type leptons are all separately conserved. This is consistent with the observed absence[60] of processes like *v^N-* r~X*. As to direct measurements, we know that the neutral particles emitted in **r** decay are lighter than a few hundred MeV. Fritzsch[18] has pointed out that this leaves open the possibility that v_v is heavier than **r,** and that **r** decays by mixing effects into channels like *viid, vud, vve,* etc., but in order to keep the mixing angles sufficiently small to be consistent with muon conservation and universality, the ***T*** would have to be rather long-lived. However, the observed limits on the **r** lifetime now rule out this possibility, so that the **r** neutrino is lighter than a few hundred MeV, and the *r does* decay into v_T.

The observed properties of *r* decay are all consistent with the simple picture that (v, *r~)*$_L$ forms a third SU(2)xU(l) doublet. Measurements of the Michel parameter by the DELCO, SLAC-LBL, and PLUTO groups indicate a *V* minus *A* matrix element. Also, all **r** decay branching ratios are now in good agreement with theoretical expectations. In particular, the *n~v*$_T$ mode which seemed to be missing last summer is now observed to have a branching ratio compatible with the theoretical value.

The semileptonic modes *r->vX* have been the subject of a number of recent papers,[20] including several submitted to this Conference. With (y„ *z~)*$_L$ an SU(2)xU(l) doublet, the differential rate for these modes is

$$\frac{d\Gamma(\tau\to\nu_\tau X)}{dQ^2}=\frac{G_F^2\cos^2\theta_c}{32\pi m_\tau^3}\frac{(m_\tau^2-Q^2)^2(m_\tau^2+Q^2)}{Q^2}\times[\rho_V(Q^2)+\rho_A(Q^2)] \qquad (9)$$

where *Q* is the total energy of the hadrons "X" in their own center-of-mass system, and *PV,A(Q²)&VZ* the spectral functions of the vector and axial-vector currents of beta decay. In the "PCAC limit" $m_u=m_d=0$ of QCD, these functions satisfy the two spectral-function sum rules

$$\int[\rho_V-\rho_A]dQ^2/Q^2=F_\pi^2\simeq(190\,\mathrm{MeV})^2 \qquad (10)$$

$$\int[\rho_V-\rho_A]dQ^2=0 \qquad (11)$$

while *\\fiy—p$_A$]Q²dQ²* diverges. When I discussed these sum rules at the Vienna "Rochester" Conference ten years ago, it was clear that $p_v(Q^2)$ could be measured from the rate e^+e^- annihilation into hadrons, but we could only dream of being able to measure $p_A(Q^2)$. Now, using *r* decay and eq. (9), we should be able to determine p_A as well as p_v from g² = *ml* to $Q^2=m_T^2$. (To the extent that strange particles can be neglected, we can even determine p_v and p_A separately without using e⁺e" annihilation; p_v and p_A receive contributions only from states with even or odd numbers of pions, respectively.) At the present time the data only allows us to test a resonance-saturated form of eqs. (10) and (11); this yields[20] a branching ratio of 0.09 for *T-^A$_x$v$_t$,* in good agreement with the observed value of 0.10±0.03.

2. *b Quarks*[1]*

Though not definitely established, it seems reasonable to assume that the 7*(9400) and r'(lOOOO) are bound states of a new quark of charge —1/3 and its antiquark. The simplest assumption is that this *b* quark forms part of a third left-handed SU(2) x U(l) doublet. As first described by Kobayashi and Maskawa,[21] the three quark doublets may be written as

$$\begin{bmatrix}u\\d'\end{bmatrix}_L \quad \begin{bmatrix}c\\s'\end{bmatrix}_L \quad \begin{bmatrix}t\\b'\end{bmatrix}_L$$

where w, c, and *t* are quarks of definite mass and charge 2/3, and *d\ s* and *b'* are linear combinations of quarks of definite mass and charge — 1/3:

$$\begin{aligned}d'&=C_1d-S_1C_3s-S_1S_3b\\ s'&=S_1C_2d+(C_1C_2C_3-S_2S_3e^{i\delta})s\\ &\qquad+(C_1C_2S_3+S_2C_3e^{i\delta})b\\ b'&=S_1S_2d+(C_1S_2C_3+C_2S_3e^{i\delta})s\\ &\qquad+(C_1S_2S_3-C_2C_3e^{i\delta})b \qquad (12)\end{aligned}$$

$$C_i\equiv\cos\theta_i \qquad S_i\equiv\sin\theta_i \qquad i=1,2,3$$

There is here a possibility that *CP* violation may be due to the complex phase $e^{i\delta}$, which for six quarks cannot be absorbed in a redefinition of the quark fields.

The mixing angles are constrained in various ways. From the success of the universality relations among leptonic and $\Delta S=0$, 1 semileptonic decays, we know that S_1 is essentially the sine of the Cabibbo angle θ_C, and that S_3 must be fairly small. Ellis, Gaillard, and Nanopoulos[22] have estimated that $|S_3|\lesssim0.24$. More recently, on the basis of a new analysis of universality relations, Shrock and Wang[23] have given a value $|S_3|=0.28\pm0.2$. From the success of the Gaillard-5. Lee estimate[24] of the c quark mass from $m(K^\circ)-m(K^\circ)$, Ellis et ai[25] estimate that $|S_2|<0.4$. From experimental upper bounds on the reaction $\nu\mu_L\to\mu+b$, Barnett[3] estimates that $|S_3|<0.3$. Finally, if it is really true that *CP* violation arises from the phase angle δ, then the observed rate of $K_L\to\mu\mu$ would indicate that[25]

$$|S_2S_3 \sin \delta|\simeq 10^{-3}. \quad (13)$$

These estimates have important implications for the decay of hadrons containing the assumed b-quark. Quigg and Rosner estimate the decay rates[26]

$$\Gamma(b\to uX)\approx S_1^2 S_3^2/1.3\times 10^{-15}\,\text{sec} \quad (14)$$

$$\Gamma(b\to cX)\approx|C_1C_2S_3+S_2C_3e^{i\delta}|^2/4\times 10^{-15}\,\text{sec}. \quad (15)$$

If the observed *CP* violation does arise from δ, then (13), (14), and (15) yield a bound on the total ***b*** decay rate

$$\Gamma(b)\geq 2\times 10^{-11}\,\text{sec}^{-1} \quad (16)$$

At present, all we know about ***b*** decay is that tracks of "bottom" particles are not seen at Fermilab,[27] so that if the cross section for producing these particles is comparable to that for the T, then their lifetime must be shorter than about 5×10^{-8} sec. Thus we do not yet know if ***b - d*** or ***b***-*s* mixing is strong enough to account for the observed violation of *CP*.

In connection with the use of universality here, this is a good place to mention the work of Sirlin on radiative corrections.[28] In the Fermi theory of beta decay, photon exchange between protons and electrons would produce an ultraviolet divergence. This problem is cured in the gauge theory, for both γ and Z° exchange, by the natural ultraviolet cut-off provided by the W and Z° masses. With $m_Z\sim 90$ GeV and a mean quark charge $Q=1/6$, Sirlin finds a radiative correction of 3.4% to the ratio of the ^{14}O and μ decay rates, which yields a value of $\sin\theta_c$ of 0.224, in good agreement with the values 0.22 to 0.23 derived from K_{e3} and hyperon decay for small S_3. This radiative correction plays an essential role in checking universality; without it, the value of $\sin\theta_c$ derived from ^{14}O and μ decay rates would be about 0.13! In his recent work, Sirlin has been able to use current algebra to avoid the complications due to strong interactions in these calculations.

5. *More neutrinos!*

We do not know of any fundamental physical principle which determines the number of quark or lepton flavors, but at least it is possible to put experimental limits on the numbers of neutrino species. These limits are of two types, cosmological and terrestrial. In both cases, the limits exploit the property of neutral currents, that the Z° couples equally to all types of neutrino, no matter how heavy are the charged leptons with which they are associated.

The cosmological limit arises from considerations of helium synthesis. If there had been a large number of neutrino flavors present during the first few seconds, then the energy density would have been greater, so the universe would have been expanding faster, less time would have been available for neutrons to turn into protons, and hence more helium would have been formed at the end of the first three minutes. In this way, Steigman, Schramm, and Gunn[29] find that for a cosmological helium abundance <26%, there cannot be more than 3 to 4 neutrino flavors.

It is important to be clear as to what particles are included as "neutrinos" in the above limit. The relevant particles are those which would have been about as abundant as ν_e's or photons during the first few seconds, when the temperature was above about 300 keV, and most of the conversion of neutrons into protons is believed to have taken place. Such particles can be of either of two exclusive types:

(a) Particles whose collision rate became less than the cosmic expansion rate at a "freezing" temperature $T^*>300$keV. In this case, it is necessary that T^* be less than about 100 MeV to 1 GeV, because the annihilation of hadrons and muons at temperatures between 1 GeV and 100 MeV raised the temperature of the other particles (γ, e^-, e^+, ν_e, etc.), so that any particle that had frozen out of equilibrium before this annihilation occurred would afterwards have made a relatively small contribution to the total energy density. It is also necessary that these particles be massless or have masses $m < T^*$, so that they would have been as abundant as photons and ordinary neutrinos when they froze out of equilibrium. Finally, it is necessary that they be stable or have lifetimes longer than a few seconds, so that they would have survived until $n \to p$ conversion occurred.

(b) Particles whose collision rate remained greater than the cosmic expansion rate at least until the temperature dropped below about 300 keV. In this case, it is necessary that the particles have masses below about 300 keV, so that they would have been about as abundant as photons and ordinary neutrinos at the time of $n \to p$ conversion. However, they could have any lifetime.

For instance, gravitons are not counted in the limit on "neutrino" types, because they froze out of thermal equilibrium very early, long before the ordinary hadrons and leptons began to annihilate. Semi-weakly-interacting particles could fall in category (b) if their mass is below 300 keV.

The known neutrinos ν_e, ν_τ fall in category (a), because they all froze out of thermal equilibrium at $T^* \sim 1$ MeV. (Even though it was much too cold then to allow charged current processes like $\nu_\mu e^- \to \nu_e \mu^-$ or $\nu_\tau e^- \to \nu_e \tau^-$, thermal equilibrium would have been maintained down to $T \sim 1$ MeV by neutral current processes like $\nu_\mu \bar{\nu}_\mu \leftrightarrow e^- e^+ \leftrightarrow \nu_\tau \bar{\nu}_\tau$.) Note that if right-handed neutrinos existed, then they too would have to be included in the upper limit on neutrino flavors.[30] The only exception would be if they froze out of equilibrium at a temperature $T^* > 100$ MeV to 1 GeV. The neutrino collision rate varies as T^5, while the cosmic expansion rate varies as T^2, so in order for neutrinos to have frozen out of equilibrium at $T^* = 100$ MeV to 1 GeV instead of $T^* = 1$ MeV, it could be necessary for their cross sections to be about 10^6 to 10^9 times smaller than usual. Putting aside this possibility, the cosmological upper limit on the number of neutrino flavors already makes it unlikely that there are right- as well as left-handed neutrinos.

There are also limits on the number of neutrino types, provided by purely terrestrial experiments. These limits again use the fact that the Z° couples equally to all neutrino species, irrespective of how heavy the associated charged leptons may be. Thus the rate for a neutral current transition $A \to B\nu\bar{\nu}$ is proportional to the total number N_ν of neutrino flavors, and may approach empirical limits if this number is large. For instance, Ma and Okada[31] estimate that the ratio of the rates for $e^+e^- \to \gamma\nu\bar{\nu}$ and $e^+e^- \to 3\gamma$ is of order $(G_F^2 s^2/\alpha^2 \pi^2)N_\nu$, or $2\times10^{-3} N_\nu$ for $\sqrt{s} = 10$ GeV. An upper limit of 10% on this ratio would set a limit $N_\nu < 50$ on the number of neutrino flavors. Similarly, we could imagine sitting on the Υ' resonance at PETRA, CESR, or PEP, and looking for the decay chain $\Upsilon' \to \Upsilon\pi\pi$, $\Upsilon \to \nu\bar{\nu}$. The ratio of $\Upsilon \to \nu\bar{\nu}$ and $\Upsilon \to e^-e^+$ can be estimated as[32]

$$\frac{\Upsilon \to \nu\bar{\nu}}{\Upsilon \to e^-e^+} = \frac{9G_F^2 m_\Upsilon^4 N_\nu}{16\pi^2\alpha^2}\left(-\frac{1}{2} + \frac{2}{3}\sin^2\theta\right)^2 \simeq 1.2\times10^{-4} N_\nu. \tag{17}$$

This does not appear very useful as a means of providing a limit on N_ν, but it might be more promising for bound states of even heavier quarks. At any rate, it is nice to know from the fact that $\nu\bar{\nu}$ emission does not dominate over electromagnetic processes that there is *some* upper limit on the number of neutrino flavors.

§V. Scalar Fields

Up to this point, I have left open the question of the number of doublets of scalar fields. No matter how many doublets there are, one still gets the same successful formula $m_Z = m_W / \cos\theta$ for the mass of the Z°, which sets the scale of neutral current coupling strengths. The phenomenological differences between having one scalar doublet or several scalar doublets are more subtle; this section will deal with some of them.

(a) *Higgs spectrum*

For one scalar doublet, there is just one physical Higgs boson, a neutral particle $H°$. For N scalar doublets, there are $4N-3$ physical Higgs bosons, of which $2N-2$ have charges ±1, and $2N-1$ are neutral.

(b) *Higgs masses*

For one scalar doublet, vacuum stability sets a lower bound on the Higgs boson mass[34]

$$m_H > \frac{\alpha}{\sin^2\theta}\left[\frac{3(2+\sec^4\theta)}{16\sqrt{2}\,G_F}\right]^{1/2} \tag{18}$$

For $\sin^2\theta$ in the range of 0.20 to 0.25, this lower bound is in the range of 7.4 to 6.1 GeV. With several scalar doublets, (18) only gives a lower bound on the mass of the *heaviest* Higgs boson; in fact if the scalar part of the Lagrangian happened to have an "accidental" symmetry which is not shared by the Yukawa couplings, then the corresponding pseudo-Goldstone Higgs boson would be quite light. Whether there is one or several scalar doublets, the Higgs boson masses must be below about 1 TeV in order to keep scalar self couplings weak.[35] If the Lagrangian is scale invariant, then for one scalar doublet the *H*° has a mass given by \AT times the expression (18),[36] and even for arbitary numbers of scalar doublets, there is one neutral boson, the "scalon," with the same mass.[37] Aside from this, it seems reasonable to expect that Higgs bosons generally have masses comparable to intermediate vector boson masses,[38] and in fact the Higgs bosons might be confused for *W's* or Z's in the first round of experiments on *W* or Z production.

(c) *CP and lepton flavor nonconservation*

For one scalar doublet, the Higgs couplings are uniquely given by the Lagrangian

$$\mathscr{L}_H = 2^{1/4} G_F^{1/2} H^0 \sum m\bar{\psi}\psi \tag{19}$$

the sum running over lepton and quark fields <*p* of definite mass *m*. This coupling conserves C, *P*, *T* and all lepton and quark flavors, so effects of virtual Higgs bosons would be very difficult to detect. In particular, with massless neutrinos and one scalar doublet the simple gauge theory would automatically conserve all lepton flavors, so that processes like *(i-+ey* would be forbidden. Also, with one scalar doublet, the only mechanism in the simple gauge theory for *CP* violation is the complex phases in the quark mixing matrix, such as *8* in eq. (12), and in consequence the neutron electric dipole moment would be very small, of order 10^{-30}ecm.[22] On the other hand, for several scalar doublets the Higgs couplings can be quite complicated, and could violate C, *P*, *T*, and/or flavor conservation. (However, the "scalon" mentioned above would have the same interaction (19) as in the case of one scalar doublet.) The violation of *CP* by Higgs boson exchange[39] is naturally "milliweak," and would give the neutron an electric dipole moment[39,40] of order 10^{-24}<?cm to 10^{-25}*e* cm. (The present experimental limits are (0.4±1.1) x 10^{-24}e cm[41] and (0.4±0.75) x 10^{-24}ecm.[42]) With several scalar doublets, Higgs exchange could produce lepton-flavor non-conserving processes. The present experimental limits on these processes are (at the 90 % confidence level):

$\frac{\mu\to e\gamma}{\mu\to e\nu\bar{\nu}}$	$<3.6\times10^{-9}$	TRIUMF[43]
	$<1.1\times10^{-9}$	SIN[44]
	$<2.0\times10^{-10}$	LAMPF[45]
$\frac{\mu N\to eN}{\mu N\to \nu X}$	$<1.6\times10^{-8}$	Ref. 46
	$<1.5\times10^{-10}$	SIN[47]
$\frac{\mu\to 3e}{\mu\to e\nu\bar{\nu}}$	$<1.9\times10^{-9}$	Ref. 48

(The phenomenology of other ***ju***-+*e* processes has been studied by Kakh.[49]) From these limits we can conclude either that there is only one scalar doublet, or that there is some selection rule which only allows one scalar doublet to couple to all the leptons, or that Higgs bosons are very heavy (above about 200 GeV), or that muon conservation is a fundamental symmetry principle.

In discussing *CP* violation, I have not taken into account the problem raised in QCD by instantons. I reviewed this in detail in my talk at the Neutrinos '78 Conference,[50] so I will not go into it further here.[51]

§VL Grand Unified Theories

There is no experimental motivation for a gauge group of weak and electromagnetic interaction larger than SU(2)xU(l). Also, everything indicates that the strong interactions are described by QCD, with a gauge group SU(3). But even though there is no experimental evidence for anything beyond SU(2) x U(l) x SU(3), it is attractive to suppose that the weak electromagnetic and strong interactions are joined in a grand unified theory, based on a simple[52] gauge group G, which contains SU(2), U(l), and SU(3) as subgroups. The larger group structure might fix those physical parameters that are still left free by SU(2)xU(l)xSU(3). In a grand unified theory, the spontaneous breakdown of G into SU(3) x SU(2) x U(l) would be much stronger[53] than the breakdown of SU(2)xU(l) into the

U(l) of electromagnetism, and hence the gauge bosons "X" associated with those generators of G that are outside the algebra of SU(3)x SU(2)xU(l) would be very heavy, with ra_x> m_w. These superheavy gauge bosons would mediate a new class of "hyperweak" interactions, with effective couplings weaker than the usual weak interactions by factors m^/ra|. The topic of grand unification was assigned to Salam's talk,[54] so I will only touch on some general aspects of the subject here.

An immediate question is, how large is the mass m_x of the superheavy gauge bosons of G? For a simple group, the couplings should all become equal (up to group theoretic factors of order unity) if measured at energies of order m_x. At ordinary energies, the strong coupling g_s is of course much larger than the "electroweak" couplings *g* or *g* but it decreases logarithmically with the energy at which it is measured, so it can become of order *g, g'* at a very high energy. Hence m_x is expected to be quite large. Estimates in various sorts of grand unified gauge theory range from a "low" value[55] m_x~ 10^4 GeV up to[56] $m_x \sim 10^{16}$ GeV, and beyond. In any case, it is clear that the hyperweak interactions will be very weak indeed, and may not be detectable at all.

As already mentioned, the larger group structure of a super-unified gauge theory might serve to fix some of the physical quantities which are at present free parameters. For instance

(a) *Z°-j mixing angle*

A simple[52] grand unified gauge group can have only one free coupling parameter, so the ratio *tand=g'/g* is fixed. However, the group structure fixes this ratio at energies of order m_x; at ordinary energies, tan/9 is subject to very large renormalization effects. In one estimate,[56] with the best present value of g_s, the corrected value of $\sin^2$# is 0.20.

(b) *Quantization of e*

For any semi-simple grand unified group G, the ratios of the values of any given gauge coupling constant for different particles will be rational numbers. These ratios are unaffected by renormalization, whatever the value of m_x.

(c) *Fermion Mass Matrices*

A grand unified theory may in some cases impose relations among the mass matrices of the quarks and leptons. One example of the sort of relation we would like to be able to derive is the well-known formula for the Cabibbo angle

$$\tan^2\theta_c \simeq m_d/m_s \qquad (20)$$

whose numerical success is so far not understood.[57]

(d) *Small mass ratios*

It is noteworthy that a number of otherwise identical leptons and quarks have extremely different masses

$$m_e/m_\mu = 4.8\times10^{-3};\quad m_u/m_c \approx 4\times10^{-3};$$
$$m_d/m_b \approx 1.5\times10^{-3}.$$

This might be explained in a grand unified gauge theory if some of the superheavy gauge bosons produce transitions[58] *e<-*ju, u^c, d^b* with couplings g_x of order *e*. In this case, if e, *d, u* were massless in zeroth order, then the emission and absorption of superheavy gauge bosons would give them masses of order

$$m_e/m_\mu \approx m_d/m_b \approx m_u/m_c \approx \alpha L/\pi$$

where I is a logarithm of superheavy gauge boson mass ratios. Since this depends only on the superheavy mass ratios, we can get reasonable orders of magnitude for the fermion mass ratio even if m_x is enormous. If the same superheavy gauge boson produced transitions *e^/u* and *u^c* or ***d<^>b,*** and if it is not too heavy, then it might produce observable rare decay processes like Z)°-*/^^ or ***(bd)-+iJL***$^+$*e+*, with branching ratios of order *m^/m*$_x$.

The hope is also sometimes expressed that a grand unified gauge theory might respect a left-right symmetry, which is broken when the grand gauge group breaks down to SU(3)x SU(2) X U(l). However, we know of no necessity for such a left-right symmetry, and in fact it leads to problems in dealing with neutrinos. If a left-right symmetric theory distinguishes fermions and antifermions, then for each left-handed neutrino v_e, v_r, there must be a right-handed neutrino (as opposed to anti-neutrino) as well. This gives 6 neutrino Species, which already exceeds the cosmological limits[29,30] discussed in Section 4. (However,, as mentioned there, these limits would not apply if the cross sections of the right-handed neutrinos were less than usual neutrino cross sections by a factor 10^{-6} to 10^{-9}, which would require that the interactions of right-handed neutrinos be mediated by gauge bosons with masses above 10^2 to 10^3 times m_w.) A left-right symmetric theory also risks giving the neutrinos masses in excess of present limits.[59] Perhaps we should be satisfied with TCP, as the only really essential symmetry between right and left.

Acknowledgements

I was greatly helped in preparing this report by conversations with many colleagues, especially M. Barnett and D. V. Nanopoulos.

References

1. K. Tittel, rapporteur's talk at this Conference. Where references are not given in this section, I believe that they can be found in Tittel's report.
2. The term "simple gauge theory" is used in Section 2-5 as an abbreviation for the simple specific gauge theory of weak and electromagnetic interactions, based on the gauge group SU(2)xU(1), which is spontaneously broken down to the U(1) of electromagnetic gauge invariance. The symmetry breaking is taken to occur in the simplest possible way, by the vacuum expectation values of any number of SU(2)xU(1) doublets of scalar fields. There are any number of left-handed SU(2) x U(1) doublets of leptons and quarks, and right-handed fermion fields are taken as singlets. Wherever relevant, the strong interactions are also assumed to be described by a gauge theory such as quantum chromodynamics (QCD). Although spontaneously broken, the SU(2)xU(1) gauge symmetry is an *exact* property of the Lagrangian, which together with the requirement of renormalizability imposes tight constraints on the interactions. In consequence, all electromagnetic and charged and neutral-current weak interactions are described by the theory in terms of just a few free parameters: e, G_F, the Z°—γ mixing angle θ, and the mass matrices of the leptons and quarks. For a review of the gauge theory of weak and electromagnetic interactions, see E. S. Abers and B. W. Lee: Phys. Rpt. **9** (1973) 1. Its phenomenological implications were reviewed here by G. Altarelli and H. Fritzsch.
3. M. Barnett, talk at the Neutrinos '78 Conference, Purdue University, to be published.
4. B. C. Barish *et al:* CALT *6S-605* (1977).
5. V. Barger, T. Gottschalk, and R. J. N. Phillips: Wisconsin preprint COO-881-32 (paper 402 submitted to this Conference); J. Smith *et al.:* Stony Brook preprint ITP-SB-78-31; M. Barnett, L.-N. Chang, and N. Weiss: Phys. Rev. **D17** (1978) 2266. It is not clear whether two very high energy events can be explained by conventional mechanisms, but no more such events have been seen, and these two events may well represent a statistical fluctuation. Even if these two events were due to cascade decay of some new quark, such as *x>^d-^^~t, t^ii+vyb, b-^ii'vpc,* the rate of these very high energy events is still sufficiently small (less than 10^{-5} to 10^{-6} of all charged current events) that no conflict with universality would arise.
6. A comprehensive theoretical analysis of such experiments has been provided through the work of Morita and his colleagues at Osaka; see M. Morita, M. Nishimura, H. Ohtsubo, and J. Yamane: J. Phys. Soc. Japan **44** (1978) Suppl. 470 and earlier references quoted therein; M. Morita, M. Nishimura, and H. Ohtsubo: Phys. Letters **73B** (1978) 17; M. Kobayashi, N. Ohtsuka, H. Ohtsubo, and M. Morita: paper 205 submitted to this Conference. A search for effects that would be caused by an induced pseudotensor in the beta decay of polarized nuclei has been carried out for ^{12}B and ^{12}N at Osaka and for ^{19}Ne at Princeton. After improvements in their apparatus, both groups now find no evidence of second-class currents: K. Sugimoto, reported at the International Conference on Nuclear Structure at Tokyo^ September 1977, and F. Calaprice, private communication. For ^{19}Ne, it is possible to set an upper limit of about 10% on any difference between the observed asymmetry parameter and that produced by weak magnetism, with no second-class currents. Similar results were also found in experiments on ^{12}B at Louvain and ETH: see M. Steele *et al.: Proc. VI Int. Conf. High Energy and Nuclear Structure* (1975), and H. Brandle *et al.:* ETH preprint. (There is also evidence against second-class effects in a variety of other measurements, including the *fi-a* correlation for $A = 8$, the correlation for *A=20,* the *fi-v* correlation in ^{6}He, the ^~-^{12}C capture rate* and the ^{12}B polarization in ***JLL~-^{12}C*** capture.)
7. In the course of experiments on the G-conjugation properties of the axial current in ^{12}B and ^{12}N decay, the question was raised whether the experiment of Y. K. Lee, L. W. Mo, and C. S. Wu: Phys. Rev. Letters **10** (1963) 253 really gives a value for weak magnetism consistent with CVC when the correct Fermi function is used; see F. P. Calaprice and B. R. Holstein: Nucl. Phys. **273** (1976) 301. This experiment has recently been reanalyzed by C. S. Wu, Y. K. Lee, and L. W. Mo: Phys. Rev. Letters **39** (1977) 72, and by K. Koshigiri *et al.:* paper 206 submitted to this Conference, and repeated by W. Kaina *et al.:* Phys. Letters **70B** (1977) 411, with results in agreement with CVC.
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9. C. Baltay: rapporteur's talk at this Conference. Where references are not give in this section, I believe that they can be found in Baltary's report.
10. For recent analyses, see L. Abbott and M. Barnett: Phys. Rev. Letters **40** (1978) 1303; **M.**

Claudson, E. Paschos, and L. R. Sulak; Harvard preprint HUTP-78/A043, October 1978.

11. Post-Conference Note: A parity violation has now been found in bismuth also by the Seattle group, at the transition frequency previously studied by them; N. Fortson, private communication. The circular polarization has the expected sign, but its magnitude still appears smaller than would be expected from the Novosibirsk results. Parity violation has now also been found in thallium; E. Commins, private communication. The preliminary value of the circular dichroism in thallium agrees in sign and magnitude with the value expected on the basis of the simple gauge theory and numerical computations of thallium atomic structure.
12. A possible uncertainty in these calculations is explored in the work of J. Hiller, J. Sucher, and G. Feinberg, paper 658 submitted to the Conference. They note that the circular polarization involves expectation values which are sensitive to poorly known details of the atomic wave functions near the nucleus. Using the Schrodinger equation, it is possible to transform the operator so that its vacuum expectation value depends on the wave function over a broader region. If the wave function were exact, there would be no difference, but Hiller *et al.* find that the results can be quite different when this procedure is applied to approximate variational wave functions, at least for the light atoms studied so far.
13. R. Taylor: talk at this Conference; C. Y. Prescott *et al:* Phys. Letters **77B** (1978) 347.
14. L. Wolfenstein: Carnegie-Mellon preprint COO-3066-111.
15. The phenomenology of parity violation in nuclear physics was discussed in papers submitted to this Conference by M. Konuma and T. Oka: No. 370; V. M. Dubovik and V. S. Zamiralov: No. 406; S. Marioka and T. Ueda: No. 578.
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18. H. Fritzsch: Phys. Letters **67B** (1977) 451.
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36. S. Coleman and E. Weinberg: Phys. Rev. **D7** (1973) 1888. Also see S. Weinberg: Phys. Rev. **D7** (1973) 2887.
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53. It is not understood why there should be a "hierarchy" of scales of spontaneous symmetry breaking. It has been claimed that there are limits on the ratio of spontaneous breaking scales possible in such hierarchies: E. Gildener: Phys. Rev. **D14** (1976) 1667; also see K. T. Mahanthappa and D. G. Unger: preprint COLO-HEP-6, paper 255 submitted to this Conference. A contrary view is taken by R. N. Mohapatra and G. Senjanovic: preprint CCNY-HEP-78(6), paper 22 submitted to this Conference; I. Bars and M. Serdaroglu: preprint COO-3075-188. My conclution is that there is no theorem which limits ratios of mass scales of spontaneous symmetry breaking, and plausible constraints can in fact yield very large mass ratios.
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58. Illustrative models of this type have been considered by M. Horibe, J. Ishida and A. Sato: paper 687; T. Maehara and T. Yanagida: paper 528.
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P9a: QCD and Related Problems

Chairman : C. N. YANG

Speaker: B. SAKITA

Scientific Secretaries: A. HOSOYA
Y. HOSOTANI

P9b: Unification Theories, Supergravity and New Ideas

Chairman: R. E. MARSHAK

Speaker: A. SALAM

Scientific Secretaries: H. TERAZAWA
A. SUGAMOTO

(Wednesday, August 30, 1978; 10: 00-10: 55, 11: 15-12: 30)