THE FIRST GAUGE THEORY OF WEAK INTERACTIONS
AND THE PREDICTION OF WEAK NEUTRAL
CURRENTS

S. A. Bludman
Department of Physics, University of Pennsylvania, Philadelphia, PA 19104

UPR-532-T

Abstract

The three theoretical and historical components of the Standard Model are the exact
chiral gauge theory of weak interactions, electroweak unification, and the Higgs mechanism
for spontaneous symmetry breaking. I put into historical perspective my 1958 invention
of the first gauge theory of weak interactions, predicting weak neutral currents, and show
how the fundamental differences between global and gauge symmetries and between partial
flavour and exact gauge symmetries, emerged in the strong and weak interactions. Al-
though renormalizability is necessary for theoretical consistency, electroweak unification
was not necessary, in principle. An interesting difference appears between the $\sin^2 \theta_W = 0$
limit of the electroweak theory and the original $SU(2)_W$ gauge theory of weak interactions.
While the electroweak mixing angle might have had any value (including zero), historically
the value $\sin^2 \theta_W \sim 0.3$ actually observed in weak neutral currents gave circumstantial
support for the Standard Model and stimulated the search for $W^-$ and $Z^-$mesons.

1 INTRODUCTION

The Standard Model [1, 2, 3] contains three theoretically and historically distinct elements:
(1) A chiral gauge theory of weak interactions with an exact $SU(2)_L$ symmetry [4]; (2) The
Higgs mechanism [5] for spontaneous symmetry, giving some of the gauge bosons finite masses,
while maintaining renormalizability [6]; (3) Electroweak unification through $W^0 - B^0$ mixing
by $\sin \theta_W$ [7]. Theoretical consistency requires that a field theory be renormalizable, but not
necessarily unified: Within the Standard Model, the electroweak mixing angle, $\sin \theta_W$, could
in principle have any value, including zero.

In Section 2 of this report, I recall the history of gauge theories in the 1950’s and my own
motivation for publishing [4] the first chiral gauge theory of weak interactions, predicting weak
neutral currents of exact $V - A$ form and approximately the weak strength observed 15 years

*Talk given at the Third International Symposium on the History of Particle Physics: “The Rise of the
Standard Model”, SLAC, June 24-27, 1992.
†Supported in part by DOE Contract No. DOE-AC02-76-ERO-3071.
later \cite{8}. In Section 3, I discuss the historic development of the distinctions between global and gauge, partial and exact symmetries, in the weak and strong interactions. We will see how Goldstone mesons were originally misperceived as an obstacle to broken-symmetry in the weak interactions. In Section 4, I emphasize the theoretical and historic importance of the Higgs mechanism for symmetry breaking in theories with exact gauge symmetries and the conditional role actually played by electroweak unification. An important property of the Standard Model in the hypothetical $\sin^2 \theta_W = 0$ limit emerges, distinguishing it from a purely $SU(2)_W$ theory of weak interactions. In Section 5, I conclude that, although theoretical consistency did not require electroweak unification, historically the discovery of WNC with electroweak mixing angle $\sin^2 \theta_W \sim (0.2 - 0.3)$ provided circumstantial evidence for the Standard Model and predicted massive gauge bosons that were finally observed in 1982.

2 NON-ABELIAN GAUGE THEORY FOR THE WEAK INTERACTIONS

Pauli \cite{1} and the early successes of QED had established the importance of electromagnetic gauge invariance and how, in simple enough theories, it led to minimal electromagnetic interactions that were renormalizable. For charged vector mesons, however, minimal electromagnetic interaction was ambiguous \cite{10} and the theory was non-renormalizable. The divergences derive from the longitudinal component of the massive vector meson field and are minimal if the gyromagnetic ratio $g = 2$ and the electric quadrupole moment $Q = -e(h/Mc)^2$. (In the Standard Model, the electroweak scale acts as a regulator for the longitudinal vector meson field, making vector meson electrodynamics renormalizable for just these electromagnetic moments.)

I had always been impressed by the Noether's Second Theorem. While her First Theorem asserted that global symmetries of the Lagrangian implied well-known conservation laws, her Second Theorem was much more powerful: local Lagrangian symmetries implied new (gauge) fields. This, together with the Yang-Mills theory \cite{11}, led to my first publication entitled “Extended Isotopic Spin Invariance and Meson-Nucleon Coupling ” \cite{12}, which showed that the then-current pion- nucleon interaction could not be derived directly from a gauge principle. Because I was always motivated only by exact gauge symmetries \cite{13}, I did not think to make the axial current partially conserved, or the pseudoscalar pion a pseudo-Goldstone meson. While approximate flavour $SU(3)$ gauge symmetries led Sakurai \cite{14} to hadronic vector mesons, we now realize that only colour is an exact hadronic symmetry and that the approximate flavour symmetries derive from the mass hierarchy of quarks in QCD.

Once the experimental situation clarified in 1957, Sudarshan and Marshak \cite{15}, Feynman and Gell-Mann \cite{16} and Sakurai \cite{17} each immediately presented their own derivations of the $V - A$ $\beta$-decay interaction. My own derivation \cite{4} followed from what I called Fermi gauge invariance, generated by charge-raising and -lowering chiral Fermi charges $F^+, F^-$. If the algebra of generators is to close, then neutral Fermi charges $2iF^0 = [F^+, F^-]$ are required, i.e. $SU(2)_L$ is the minimal symmetry of the Fermi interactions. I went on to impose this symmetry locally and was led to an $SU(2)_L$ triplet of gauge bosons, $W_{\pm}, 0$, coupled to a triplet of chiral Fermi currents $F_{\mu \pm, 0}$. This chiral gauge theory predicted weak neutral currents of exact $V - A$
form and the same strength as the weak charged currents. The observed strength of the Fermi interactions, $G_F/\sqrt{2} = g^2/8M_W$, then required, in tree approximation, $M_W = gv/2$, where $v \equiv (\sqrt{2}G_F)^{-1/2} = 246$ GeV. Neither $g$ nor $M_W$ was predicted separately, but if $g \sim 1$, $M_W \sim 100$ GeV was to be expected.

No attempt was made to provide a mechanism for giving the intermediate vector bosons mass, to unify weak with electromagnetic interactions, or to explain the absence of flavour-changing weak neutral currents. Flavour-changing WNC were known to be absent to $O(10^{-8})$ and even flavour-preserving WNC were incorrectly reported [18] to be at least thirty times weaker than charged weak neutral currents. Faith in quarks and in quark-lepton symmetry soon led Glashow et al.[31] to propose the GIM mechanism, explaining the absence of flavour-changing WNC at tree-level and reducing their radiatively-induced amplitude at $O(G_F\alpha)$ by a suitably large factor $(m_c^2 - m_u^2)/M_W^2$.

My 1958 paper was soon followed by proposals [19, 20, 21] to use accelerator neutrino beams to search for flavour-preserving weak neutral currents. But this search remained very difficult, because of high backgrounds for neutrino-induced charged-current processes in which muons escaped undetected which were hard to estimate. In any case, neutrino experimentalists in the 1960’s were preoccupied with deep inelastic scattering at SLAC and scaling.

These experimental difficulties, together with the need for a consistent theory allowing massive gauge bosons, suggest why chiral weak neutral currents needed to wait from 1958 to 1973 for experimental confirmation.

3 SPONTANEOUSLY BROKEN GLOBAL SYMMETRIES

The idea of spontaneous symmetry breaking (SSB), better denominated hidden symmetry, was brought from condensed matter physics to quantum field theory by Heisenberg [22] and Nambu [23] and soon led to the Goldstone Theorem [24, 25]. Klein and I identified the Goldstone bosons expected from different levels of global symmetry-breaking and emphasized that Goldstone bosons were not present in theories with long-range interactions. The Goldstone Theorem showed how SSB could produce long-range interactions out of a short-range theory. Following Anderson [26], we suggested that, conversely, long-range interactions might be converted into short-range. But we missed the Higgs mechanism which differentiates between the role of Goldstone mesons in gauge theories and their role in global symmetry theories.

In the weak interactions, Klein and I observed there were apparently no Goldstone bosons and that, although the neutrino was apparently massless, it could not be a Goldstone meson, because the vacuum could not be macroscopically occupied by fermions. Because we failed to associate the Goldstone Theorem with my earlier proposal of a gauge theory of weak interactions, Goldstone mesons were misperceived as obstacles to a theory of weak interactions.

The 1958 work on chiral invariance was cited by Gell-Mann and by Nambu [27] and ultimately led to current algebras, soft-pion theorems, PCAC and the Goldberger-Treiman relation. These heuristic successes, however, tended to gloss over the fundamental differences between global and gauge symmetries, and between partial flavour symmetries and exact gauge symmetries, in the strong and weak interactions.

Exact symmetries were useful in classifying fields and particles and were most aesthetically
satisfying. For these reasons, I tended to avoid hadron physics and concentrated on weak interactions where, I was convinced, exact symmetries were to be found. At his time, I left the University of California Radiation Laboratory (now the Lawrence Berkeley Laboratory), which was then dominated by dispersion relations and S-matrix theory. I took an academic position at the University of Pennsylvania and my interests gradually shifted from laboratory to astrophysical particle physics.

4 SPONTANEOUSLY BROKEN GAUGE SYMMETRIES, WITH AND WITHOUT UNIFICATION

Unlike earlier global theories of the strong interactions [13], my 1958 theory of the weak interactions was an exact (chiral) gauge theory. The power of an exact gauge symmetry is that, if symmetry is spontaneously broken by the Higgs mechanism [26, 5], giving some gauge bosons masses, the symmetry remains hidden and the theory remains renormalizable. Indeed, the Standard Model has only exact gauge symmetries, massless gauge bosons are usually not manifest: Either the (colour) gauge symmetry is unbroken, but the massless gluons are confined, or the gauge symmetry is spontaneously broken, providing masses for the gauge bosons.

Weinberg [28] and Salam [29] proposed the Electroweak Standard Model, conjecturing that the theory would remain renormalizable. Nevertheless, the 1967 Weinberg paper was referred to by no one (including Weinberg) in 1967-70 and only once in 1971 [30]. Finally, ‘t Hooft [6] proved that such a theory remained renormalizable. In this way, a complete theory of massive charged vector mesons and of weak interactions was achieved [1, 2, 3].

In the minimal Standard Model, the couplings enter through the $SU(2)_L \times U(1)_Y$ covariant derivative $D_\mu = \partial_\mu - ig T \cdot W_\mu - ig'(Y/2)B_\mu$.

(1) The Higgs mechanism gives the vector mesons (generally) unequal masses $M_W = M_Z \cos \theta_W$, where $g'/g \equiv \tan \theta_W$. (2) The charged vector mesons couple to the electromagnetic field with magnetic moment $2(e/2Mc)$ and electric quadrupole moment $-(h/Mc)^2$; (3) the WNC couple to $Z^0$ with coupling constant $g/\cos \theta_W$; (4) Charged particle currents couple to the electromagnetic field with coupling constant $e \equiv g \sin \theta_W \equiv g' \cos \theta_W$. Consequently, in tree approximation,

$$M_W \sin \theta_W = M_Z \sin \theta_W \cos \theta_W = (e/2)(\sqrt{2}G_F)^{-1/2} = \sqrt{\pi \alpha v} \equiv A_0 = 37.3 \text{ GeV.} \quad (1)$$

For consistency, a quantum field theory needs to be renormalizable, but need not be unified. In principle, we could have had either spontaneously broken $U(1)$ symmetry with no weak currents ($g = 0$, $g' = e$, Schwinger’s electrodynamics with massive photons [12]) or weak $SU(2)_L$ symmetry ($g' = 0 = e$, WNC with coupling constant $g$ [3]). These two examples illustrate, contrary to ref. [1], the logical possibility of consistent (renormalizable) theories without unification.

The electromagnetic field exists and $B^0$ and $W^0$ mix, but how Nature chooses $\sin^2 \theta_W = 0.23$ ($e \leq g' \leq g < 1$), remains unexplained within the Standard Model. In the minimal Electroweak Model, besides $G_F$ and $e$, there is only one free parameter,

$$\sin^2 \theta_W \equiv (M_Z^2 - M_W^2)/M_Z^2 = (1/2)[1 - \sqrt{1 - (2A_0/M_Z)^2}], \quad (2)$$
in tree approximation, which measures the $SU(2)_L$ symmetry breaking through $W^0 - B^0$ mixing. In a unified theory, $g, g' \geq e$, so that $M_W \geq 37 \text{ GeV}$, $M_Z \geq 74 \text{ GeV}$. This leads to an interesting difference between a pure $SU(2)_W$ theory and the $\sin^2 \theta_W \rightarrow 0$ limit of the Electroweak Theory. In the former, only the ratio $M_W/g = 123 \text{ GeV}$ is constrained. In the latter, holding $G_F, e$ constant as $\sin^2 \theta_W \rightarrow 0$, makes $g' \rightarrow e$ and $g, M_W = M_Z$ diverge. The $\sin^2 \theta_W = 0$ limit of a unified theory would be one with tree-approximation point-interactions, which is unitary and renormalizable because of huge radiative corrections!

For energies $\gg 10 \text{ GeV}$, the mass differences between W- and Z-mesons and among the quarks (other than the top quark) can be neglected and the original $SU(2)_L$ symmetry is restored. This old theory will then be a good approximation to leptonic and semi-leptonic processes, other than top quark decay. Thus, the effects of unification practically disappear already at energies $\gg 10 \text{ GeV}$ much lower than the unification scale at which symmetry-breaking disappears.

5  **HISTORICAL CONCLUSIONS**

The proof that, in an exact gauge theory, renormalizability would be retained even as the gauge mesons acquired mass by the Higgs mechanism, immediately convinced theorists and experimentalists of the Electroweak Standard Model. Although a consistent theory without electroweak is possible, in principle, the discovery of weak neutral currents [8] with mixing $\sin^2 \theta_W \sim 0.3$, gave circumstantial evidence for the Standard Model and predicted $M_W \approx 80 \text{ GeV}, M_Z \approx 90 \text{ GeV}$. The ultimate discovery [33] of these gauge bosons with unequal masses directly confirmed the Standard Model.

**References**

[1] S. L. Glashow  *Rev. Mod. Phys.* **52**, 539, 1980.

[2] A. Salam  *Rev. Mod. Phys.* **52**, 525, 1980.

[3] S. Weinberg  *Rev. Mod. Phys.* **52**, 515, 1980.

[4] S. A. Bludman,  *Nuovo Cimento* **9**, 433, 1958.

[5] P. W. Higgs,  *Phys. Lett.* **12**, 132, 1964; **13**, 508, 1964;  *Phys. Lett.* **145**, 1156, 1966; F. Englert and R. Brout,  *Phys. Rev. Lett.* **13**, 321, 1964; T. W. Kibble,  *Phys. Lett.* **155**, 1554, 1967; G. S. Guralnik, C. R. Hagen and T. W. B. Kibble,  *Phys. Rev. Lett.* **13**, 585, 1964.

[6] G. ’t Hooft,  *Nucl. Phys.* **B 35**, 167, 1971; G. ’t Hooft and M. Veltman,  *Nucl. Phys.* **B 44**, 189, 1972, **B 50**, 318, 1972; B. W. Lee and J. Zinn-Justin,  *Phys. Rev.* **D 5**, 3121, 3137, 3155, 1972.

[7] S. L. Glashow,  *Nucl. Phys.* **22**, 579, 1961.
[8] F. J. Hasert et al., Phys. Lett. 46B, 138, 1973; A. Benvenuti et al., Phys. Rev. Lett. 32, 800, 1974.

[9] W. Pauli, Rev. Mod. Phys. 13, 203, 1941.

[10] J. A. Young and S. A. Bludman, Phys. Rev. 131, 2326, 1963; G. Feinberg, Phys. Rev. 110, 1482, 1958; T. Kuo-Hsien, C.R. Acad. Sci. (Paris) 245, 289, 1957.

[11] C. N. Yang and R. L. Mills, Phys. Rev. 96, 191, 1954.

[12] S. A. Bludman, Phys. Rev. 100, 372, 1955.

[13] Many earlier authors, N. Kemmer, Phys. Rev. 52, 906, 1937; G. Gamow and E. Teller, Phys. Rev. 51, 288, 1937; G. Wentzel, Helv. Phys. Acta 10, 108, 1937 had proposed global SU(2) symmetries for the strong interactions.

[14] J. Sakurai, Ann. Phys. 11, 1, 1960.

[15] E. C. G. Sudarshan and R. E. Marshak, Padua-Venice International Conference, September, 1957; Phys. Rev. 109, 1860, 1958.

[16] R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193, 1958.

[17] J. Sakurai, Nuovo Cimento 4, 649, 1958.

[18] M. M. Block et al, Phys. Lett. 12, 1964; Perkins group report at Sienna Conference, 1963.

[19] T. D. Lee and C. N. Yang, Phys. Rev. Lett. 4, 30, 1960.

[20] B. Pontecorvo, Phys. Lett. 1, 287, 1962.

[21] S. S. Gershtein et al, J. Exptl. Theoret. Phys. (U.S.S.R.) 43, 1554, 1962.

[22] W. Heisenberg, Zeitschr. f. Naturf. 14, 441, 1959.

[23] Y. Nambu, Phys. Rev. Lett. 4, 380, 1960; Y. Nambu and G. Jona Lasinio, Phys. Rev. 122, 345, 1961; 124, 246.

[24] J. Goldstone, Nuovo Cimento 19, 154, 1961; J. Goldstone, A. Salam and S. Weinberg, Phys. Rev. 127, 965, 1962; J. C. Taylor, Proc. 1962 Intl. Conf. on High-Energy Physics (CERN, Geneva, 1962).

[25] S. A. Bludman and A. Klein, Phys. Rev. 131, 2364, 1963.

[26] P. W. Anderson, Phys. Rev. 130, 439, 1962.

[27] M. Gell-Mann, Proc. 1960 Annual Intl. Conf. on High-Energy Physics at Rochester (Interscience Publishers, Inc., New York, 1960); Y. Nambu and D. Lurié, Phys. Rev. 125, 1429, 1962.
[28] S. Weinberg, *Phys. Rev. Lett.* **19**, 1264, 1967.

[29] A. Salam, *Elementary Particle Theory* (ed. N. Svartholm, Almqvist & Wiksells, Stockholm, 1968).

[30] S. Coleman, *Science* **206**, 1290, 1979.

[31] S. L. Glashow, J. Iliopoulos and L. Maiani, *Phys. Rev. D* **2** 1285, 1970.

[32] J. Schwinger, *Phys. Lett.* **125**, 397, 1962.

[33] G. Arnison *et al.*, *Phys. Lett.* **122B**, 103, 1983, **126B**, 398, 1983; M. Banner *et al.*, *Phys. Lett.* **122B**, 476, 1983; P. Bagnaia *et al.*, *Phys. Lett.* **129B**, 130, 1983.