

# On the $W^\pm$ and $Z^0$ Masses

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## Abstract

Scalar and vector fields are coupled in a gauge invariant manner, such as to form massive vector fields. The nonlinear equations of motion admit transverse and longitudinal solutions. These are shown to conserve energy and momentum. The mass ratio  $m_W/m_Z$  is determined.

## 1. Introduction

The U(1) model of scalar electrodynamics has been used to create massive photons. However, it was only with the advent of electroweak theory that the weak constants,  $g$  and  $g'$ , were thought to play a similar role. In this paper, the weak coupling between scalar and vector fields is shown to generate mass. The coupling terms occur in the standard electroweak Lagrangian. They give rise to nonlinear equations of motion. Transverse and longitudinal solutions are found for the  $W^\pm$  and  $Z^0$  bosons. Total energy and momentum are shown to be conserved. The mass ratio  $m_W/m_Z$  emerges, during the course of this calculation.

The paper begins by revisiting (and revising) the U(1) model. Most of the analysis carries over to the electroweak theory.

## 2. U(1): Equations of Motion

The U(1) Lagrangian is

$$L = L(A) + L(\Phi) + L(k^2) \quad (1)$$

where

$$L(A) = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad (2)$$

$$L(\Phi) = g^{\mu\nu}(D_\mu\Phi)^*(D_\nu\Phi) \quad (3)$$

$$L(k^2) = -\frac{k^2}{6g^2}g^{\mu\nu}k_\mu k_\nu \quad (4)$$

The constant term  $L(k^2)$  does not enter the field equations, but it will contribute to the energy tensor. The U(1) covariant derivatives are

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \quad (5)$$

$$D_\mu\Phi = \partial_\mu\Phi + igA_\mu\Phi \quad (6)$$

The functional derivatives are

$$\frac{\partial L}{\partial(\partial_\mu A_\nu)} = -F^{\mu\nu} \quad (7)$$

$$\frac{\partial L}{\partial A_\nu} = 2g^2 A^\nu \Phi^* \Phi + ig\{(\partial^\nu \Phi^*)\Phi - \Phi^* \partial^\nu \Phi\} \quad (8)$$

$$\frac{\partial L}{\partial(\partial_\mu \Phi^*)} = \partial^\mu \Phi + igA^\mu \Phi \quad (9)$$

$$\frac{\partial L}{\partial \Phi^*} = g^2 A_\mu A^\mu \Phi - igA^\mu \partial_\mu \Phi \quad (10)$$

The equations of motion for the vector field are

$$-\partial_\mu F^{\mu\nu} = 2g^2 A^\nu \Phi^* \Phi + ig\{(\partial^\nu \Phi^*)\Phi - \Phi^* \partial^\nu \Phi\} \quad (11)$$

while for the scalar field

$$\partial_\mu \partial^\mu \Phi = g^2 A_\mu A^\mu \Phi - ig\{(\partial_\mu A^\mu)\Phi + 2A^\mu \partial_\mu \Phi\} \quad (12)$$

The U(1) gauge invariance allows the transformation

$$\Phi = \frac{1}{\sqrt{2}}(\phi + i\psi) \longrightarrow \frac{1}{\sqrt{2}}\phi \quad (13)$$

where  $\phi(x)$  is a real function.[1] In this unitary gauge, the equations of motion become

$$\partial_\mu F^{\mu\nu} + g^2 A^\nu \phi^2 = 0 \quad (14)$$

$$\partial_\mu \partial^\mu \phi - g^2 A_\mu A^\mu \phi = 0 \quad (15)$$

$$(\partial_\mu A^\mu)\phi + 2A^\mu \partial_\mu \phi = 0 \quad (16)$$

Since  $\partial_\mu \partial_\nu F^{\mu\nu} \equiv 0$ , it follows from (14) that

$$\partial_\mu (A^\mu \phi^2) = 0 \quad (17)$$

which agrees with (16). These equations admit traveling solutions, if  $A^\mu$  is a polarized vector. In this case,

$$A^\mu(u) = \epsilon^\mu f(u) \quad (18)$$

where the argument  $u = -k_\mu x^\mu$ , and  $\epsilon^\mu$  is a real polarization vector. <sup>1</sup> Such vectors satisfy

$$\partial_\mu A^\mu(u) = -k_\mu \epsilon^\mu \frac{df(u)}{du} = 0 \quad (19)$$

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<sup>1</sup>Throughout this paper,  $u = -k_\mu x^\mu = (\mathbf{k} \cdot \mathbf{x} - k^0 x^0)$  and  $k^2 = k_\mu k^\mu = (k^0)^2 - \mathbf{k}^2$ .

since  $k_\mu \epsilon^\mu = 0$ . From (16), it must also be true that

$$A^\mu \partial_\mu \phi = 0 \quad (20)$$

This condition is satisfied, if  $\phi = \phi(u)$

$$A^\mu \partial_\mu \phi = -k_\mu \epsilon^\mu f(u) \frac{d\phi}{du} = 0 \quad (21)$$

Polarization vectors are space-like,  $\epsilon_\mu \epsilon^\mu = -1$ , so that

$$A_\mu A^\mu = -f^2(u) \quad (22)$$

Therefore, both equations (14) and (15) will be satisfied, if  $f(u) = \phi(u)$  and

$$\partial_\mu \partial^\mu \phi(u) + g^2 \phi^3(u) = 0 \quad (23)$$

This equation, known as the cubic wave equation, is solved by the elliptic function  $\text{cn}(u, \frac{1}{2})$  (appendix A)

$$\phi(u) = \frac{k}{g} \text{cn}(-k_\mu x^\mu) \quad (24)$$

The amplitude of this traveling wave is not arbitrary, but is fixed by the value of  $k/g$ .

### 3. U(1): Energy and Momentum

The energy tensor for the vector field is

$$T_{\mu\nu}(A) = F_{\mu\eta} F^\eta{}_\nu + \frac{1}{4} g_{\mu\nu} F_{\eta\rho} F^{\eta\rho} \quad (25)$$

with energy and momentum densities

$$T_{00}(A) = \frac{1}{2} \{ F_{01}^2 + F_{02}^2 + F_{03}^2 + F_{23}^2 + F_{31}^2 + F_{12}^2 \} \quad (26)$$

$$T_{0i}(A) = F_{01} F_{i1} + F_{02} F_{i2} + F_{03} F_{i3} \quad (27)$$

For the real scalar field

$$T_{\mu\nu}(\phi) = \partial_\mu \phi \partial_\nu \phi + g^2 A_\mu A_\nu \phi^2 - g_{\mu\nu} L(\phi) \quad (28)$$

The energy and momentum densities are

$$T_{00}(\phi) = \frac{1}{2} \left\{ (\partial_0 \phi)^2 + (\nabla \phi)^2 + g^2 [(A_0)^2 + \mathbf{A}^2] \phi^2 \right\} \quad (29)$$

$$T_{0i}(\phi) = \partial_0 \phi \partial_i \phi + g^2 A_0 A_i \phi^2 \quad (30)$$

The constant term  $L(k^2)$  contributes

$$T_{\mu\nu}(k^2) = -\frac{k^2}{3g^2} (k_\mu k_\nu - \frac{1}{2} g_{\mu\nu} k^2) \quad (31)$$

so that

$$T_{00}(k^2) = -\frac{k^2}{6g^2} (k_0^2 + \mathbf{k}^2) \quad (32)$$

$$T_{0i}(k^2) = -\frac{k^2}{3g^2} k_0 k_i \quad (33)$$

The following formulas occur repeatedly in the calculations and are placed here for reference (app. A):

$$\phi^2 = \frac{k^2}{g^2} \text{cn}^2(u) \quad (34)$$

$$(\phi')^2 = \frac{k^2}{2g^2} \{1 - \text{cn}^4(u)\} \quad (35)$$

#### (a) Transverse polarization

For plane waves moving along the  $x^3$ -axis,  $k^\mu = (k^0, k^3)$ , and the linear polarization vectors are

$$\epsilon_1^\mu = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} \quad \epsilon_2^\mu = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} \quad (36)$$

If the polarization is along  $x^1$ , then  $A^\mu = \epsilon_1^\mu \phi(u)$  has the single component  $A^1 = \phi(u)$ . In this case, the energy contributions are

$$\begin{aligned} T_{00}(A) &= \frac{1}{2} (\partial_0 A_1)^2 + \frac{1}{2} (\partial_3 A_1)^2 = \frac{k_0^2 + k_3^2}{2} (\phi')^2 \\ &= \frac{k^2}{2g^2} \frac{k_0^2 + k_3^2}{2} \{1 - \text{cn}^4(u)\} \end{aligned} \quad (37)$$

$$\begin{aligned}
T_{00}(\phi) &= \frac{1}{2} \left\{ (\partial_0 \phi)^2 + (\partial_3 \phi)^2 + g^2 A_1^2 \phi^2 \right\} \\
&= \frac{k^2}{2g^2} \left\{ \frac{k_0^2 + k_3^2}{2} \{1 - \text{cn}^4(u)\} + (k_0^2 - k_3^2) \text{cn}^4(u) \right\} \quad (38)
\end{aligned}$$

$$T_{00}(k^2) = -\frac{k^2}{2g^2} \frac{k_0^2 + k_3^2}{3} \quad (39)$$

Similarly, the momentum contributions are

$$T_{03}(A) = \partial_0 A_1 \partial_3 A_1 = \frac{k^2}{2g^2} k_0 k_3 \{1 - \text{cn}^4(u)\} \quad (40)$$

$$T_{03}(\phi) = \partial_0 \phi \partial_3 \phi = \frac{k^2}{2g^2} k_0 k_3 \{1 - \text{cn}^4(u)\} \quad (41)$$

$$T_{03}(k^2) = -\frac{k^2}{2g^2} \frac{2}{3} k_0 k_3 \quad (42)$$

Sum the energy and momentum contributions to find

$$T_{00} = \frac{k^2}{2g^2} \left\{ \frac{2}{3} (k_0^2 + k_3^2) - 2k_3^2 \text{cn}^4(u) \right\} \quad (43)$$

$$T_{03} = \frac{k^2}{2g^2} k_0 k_3 \left\{ \frac{4}{3} - 2 \text{cn}^4(u) \right\} \quad (44)$$

The energy and momentum integrations may be performed, with the introduction of the volume element  $l^3 dV/V$ . In order to arrive at the correct quantum expressions, the integrals must be independent of the ratio  $k^2/g^2$ . This factor is eliminated by setting

$$\frac{l^3}{V} dV = \frac{3\pi}{2K} \frac{g^2}{k^2 k^0 V} dV \quad (45)$$

The integrals are

$$\begin{aligned}
E &= \frac{3\pi}{2K} \frac{g^2}{k^2 k^0 V} \int T_0^0 dV \\
&= \frac{3\pi}{2K} \frac{\hbar c}{2k^0 V} \int \left\{ \frac{2}{3} (k_0^2 + k_3^2) - 2k_3^2 \text{cn}^4(u) \right\} dV \quad (46)
\end{aligned}$$

$$\begin{aligned}
cp^3 &= \frac{3\pi}{2K} \frac{g^2}{k^2 k^0 V} \int T_0^3 dV \\
&= \frac{3\pi}{2K} \frac{\hbar c}{2k^0 V} \int k_0 k_3 \left\{ \frac{4}{3} - 2 \text{cn}^4(u) \right\} dV \quad (47)
\end{aligned}$$

The elliptic function  $\text{cn}(u, \frac{1}{2})$  admits the integral (app. A)

$$\int \text{cn}^4(u) du = \frac{u}{3} + \frac{2}{3} \text{sn}(u)\text{cn}(u)\text{dn}(u) + \text{constant} \quad (48)$$

Over one period,

$$\frac{1}{4K} \int_0^{4K} \text{cn}^4(u) du = \frac{1}{3} \quad (49)$$

Therefore, the energy and momentum are constants of the motion

$$E = \frac{\pi}{2K} \hbar c k^0 = \hbar \omega \quad (50)$$

$$cp^3 = \frac{\pi}{2K} \hbar c k^3 = \hbar c \frac{2\pi}{\lambda} \quad (51)$$

**(b) Longitudinal polarization**

In this case,  $A^\mu(u) = \epsilon^\mu \phi(u)$  is expressed in terms of the zero-helicity vector

$$\epsilon^\mu(0) = \frac{1}{k} \begin{pmatrix} k^3 \\ 0 \\ 0 \\ k^0 \end{pmatrix} \quad (52)$$

$A^\mu$  has two components  $(A^0, A^3) = (k^3, k^0)k^{-1}\phi(u)$ . The contributions to the energy density are

$$T_{00}(A) = \frac{1}{2}(\partial_0 A_3 - \partial_3 A_0)^2 = \frac{k^2}{2g^2} \frac{k_0^2 - k_3^2}{2} \{1 - \text{cn}^4(u)\} \quad (53)$$

$$\begin{aligned} T_{00}(\phi) &= \frac{1}{2} \{(\partial_0 \phi)^2 + (\partial_3 \phi)^2 + g^2(A_0^2 + A_3^2)\phi^2\} \\ &= \frac{k^2}{2g^2} \frac{k_0^2 + k_3^2}{2} \{1 + \text{cn}^4(u)\} \end{aligned} \quad (54)$$

$$T_{00}(k^2) = -\frac{k^2}{2g^2} \frac{k_0^2 + k_3^2}{3} \quad (55)$$

while those for the momentum are

$$T_{03}(A) = 0 \quad (56)$$

$$T_{03}(\phi) = \partial_0\phi \partial_3\phi + g^2 A_0 A_3 \phi^2 = \frac{k^2}{2g^2} k_0 k_3 \{1 + \text{cn}^4(u)\} \quad (57)$$

$$T_{03}(k^2) = -\frac{k^2}{2g^2} \frac{2}{3} k_0 k_3 \quad (58)$$

Sum terms to find

$$T_{00} = \frac{k^2}{2g^2} \left\{ \frac{2}{3} k_0^2 - \frac{1}{3} k_3^2 + k_3^2 \text{cn}^4(u) \right\} \quad (59)$$

$$T_{03} = \frac{k^2}{2g^2} k_0 k_3 \left\{ \frac{1}{3} + \text{cn}^4(u) \right\} \quad (60)$$

The energy and momentum integrals are

$$\begin{aligned} E &= \frac{3\pi}{2K} \frac{g^2}{k^2 k^0 V} \int T_0^0 dV \\ &= \frac{3\pi}{2K} \frac{\hbar c}{2k^0 V} \int \left\{ \frac{2}{3} k_0^2 - \frac{1}{3} k_3^2 + k_3^2 \text{cn}^4(u) \right\} dV \\ &= \frac{\pi}{2K} \hbar c k^0 = \hbar \omega \end{aligned} \quad (61)$$

$$\begin{aligned} cp^3 &= \frac{3\pi}{2K} \frac{g^2}{k^2 k^0 V} \int T_0^3 dV \\ &= \frac{3\pi}{2K} \frac{\hbar c}{2k^0 V} \int k_0 k^3 \left\{ \frac{1}{3} + \text{cn}^4(u) \right\} dV \\ &= \frac{\pi}{2K} \hbar c k^3 = \hbar c \frac{2\pi}{\lambda} \end{aligned} \quad (62)$$

#### 4. $U(1) \otimes SU(2)_L$ : Field Equations; Energy Tensors

The Lagrangian is given by

$$L = L(W) + L(B) + L(\Phi) + L(k^2) + L(\text{leptons}) \quad (63)$$

The lepton term contains the electroweak interaction and will be set aside. The focus is upon the coupling between vector and scalar fields. The covariant derivatives are [2]

$$G_{\mu\nu}(W) = \partial_\mu(W_\nu^i T^i) - \partial_\nu(W_\mu^i T^i) + g \Sigma_{ijk} \epsilon_{ijk} W_\mu^i W_\nu^j T^k \quad (64)$$

$$F_{\mu\nu}(B) = \partial_\mu B_\nu - \partial_\nu B_\mu \quad (65)$$

$$\begin{aligned}
D_\mu \Phi &= \left\{ \partial_\mu + ig T^i W_\mu^i + ig' \frac{Y}{2} B_\mu \right\} \Phi \\
&= \left\{ \partial_\mu + ig \frac{\tau^i}{2} W_\mu^i + ig' \frac{1}{2} B_\mu \right\} \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad (66)
\end{aligned}$$

The final term in  $G_{\mu\nu}(W)$  yields third- and fourth-order vector boson interactions and will also be ignored.[3] This leaves

$$\begin{aligned}
L(W) + L(B) &= -\frac{1}{2} \text{Tr} G_{\mu\nu}(W) G^{\mu\nu}(W) - \frac{1}{4} F_{\mu\nu}(B) F^{\mu\nu}(B) \\
&= -\frac{1}{4} \left\{ F_{\mu\nu}(A) F^{\mu\nu}(A) + F_{\mu\nu}(Z) F^{\mu\nu}(Z) \right. \\
&\quad \left. + F_{\mu\nu}(W^1) F^{\mu\nu}(W^1) + F_{\mu\nu}(W^2) F^{\mu\nu}(W^2) \right\} \quad (67)
\end{aligned}$$

where

$$W_\mu^3 = \frac{g'}{\sqrt{g^2 + g'^2}} A_\mu + \frac{g}{\sqrt{g^2 + g'^2}} Z_\mu = \sin \theta A_\mu + \cos \theta Z_\mu \quad (68)$$

$$B_\mu = \frac{g}{\sqrt{g^2 + g'^2}} A_\mu - \frac{g'}{\sqrt{g^2 + g'^2}} Z_\mu = \cos \theta A_\mu - \sin \theta Z_\mu \quad (69)$$

The charged bosons  $W_\mu^\pm = (W_\mu^1 \mp iW_\mu^2)/\sqrt{2}$  are expressed in terms of the real fields  $W_\mu^1$  and  $W_\mu^2$ .

The expansion of

$$L(\Phi) = g^{\mu\nu} (D_\mu \Phi)^\dagger D_\nu \Phi \quad (70)$$

is carried out in appendix B, where the functional derivatives are also found. Before writing the equations of motion, the scalar field is transformed to unitary gauge

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \longrightarrow \begin{pmatrix} 0 \\ \phi/\sqrt{2} \end{pmatrix} \quad (71)$$

where  $\phi(x)$  is real. This greatly simplifies the functional derivatives

$$\frac{\partial L}{\partial(\partial_\mu A_\nu)} = -F^{\mu\nu}(A) \quad \frac{\partial L}{\partial A_\nu} = 0 \quad (72)$$

$$\frac{\partial L}{\partial(\partial_\mu Z_\nu)} = -F^{\mu\nu}(Z) \quad \frac{\partial L}{\partial Z_\nu} = \frac{1}{4}(g^2 + g'^2) Z^\nu \phi^2 \quad (73)$$

$$\frac{\partial L}{\partial(\partial_\mu W_\nu)} = -F^{\mu\nu}(W) \quad \frac{\partial L}{\partial W_\nu} = \frac{1}{4} g^2 W^\nu \phi^2 \quad (74)$$

where  $W_\nu$  is either  $W_\nu^1$  or  $W_\nu^2$ . The equations of motion for the vector fields are

$$-\partial_\mu F^{\mu\nu}(A) = 0 \quad (75)$$

$$-\partial_\mu F^{\mu\nu}(Z) = \frac{1}{4}(g^2 + g'^2)Z^\nu \phi^2 \quad (76)$$

$$-\partial_\mu F^{\mu\nu}(W) = \frac{1}{4}g^2 W^\nu \phi^2 \quad (77)$$

Since  $\partial_\mu \partial_\nu F^{\mu\nu} \equiv 0$ , these equations yield

$$\partial_\nu(Z^\nu \phi^2) = \partial_\nu(W^\nu \phi^2) = 0 \quad (78)$$

For the scalar field,

$$\frac{\partial L}{\partial(\partial_\mu \phi^{0*})} = \partial^\mu \phi^0 - \frac{i}{2}\sqrt{g^2 + g'^2} Z^\mu \phi^0 \quad (79)$$

$$\frac{\partial L}{\partial \phi^{0*}} = \frac{i}{2}\sqrt{g^2 + g'^2} Z^\mu \partial_\mu \phi^0 + \frac{g^2}{2} W^{-\mu} W_\mu^+ \phi^0 + \frac{1}{4}(g^2 + g'^2) Z^\mu Z_\mu \phi^0 \quad (80)$$

$$\frac{\partial L}{\partial(\partial_\mu \phi^{+*})} = \frac{i}{\sqrt{2}} g W^{+\mu} \phi^0 \quad (81)$$

$$\frac{\partial L}{\partial \phi^{+*}} = -\frac{i}{\sqrt{2}} g W^{+\mu} \partial_\mu \phi^0 + (eA^\mu - g' \sin \theta Z^\mu) \frac{1}{\sqrt{2}} g W_\mu^+ \phi^0 \quad (82)$$

The equations of motion are ( $\phi^0 = \phi/\sqrt{2}$ )

$$\partial_\mu \partial^\mu \phi - \frac{1}{4}g^2 W^{1\mu} W_\mu^1 \phi - \frac{1}{4}g^2 W^{2\mu} W_\mu^2 \phi - \frac{1}{4}(g^2 + g'^2) Z^\mu Z_\mu \phi = 0 \quad (83)$$

and

$$(eA^\mu - g' \sin \theta Z^\mu) g W_\mu^+ \phi = 0 \quad (84)$$

where (78) has been used. The vector fields couple individually with  $\phi$ , so that (84) will be satisfied.

The energy tensors are much the same as for U(1). Each vector field  $A_\mu$ ,  $W_\mu^1$ ,  $W_\mu^2$ ,  $Z_\mu$  contributes

$$T_{\mu\nu} = F_{\mu\eta} F^\eta{}_\nu + \frac{1}{4} g_{\mu\nu} F_{\eta\rho} F^{\eta\rho} \quad (85)$$

The scalar Lagrangian

$$L(\phi) = \frac{1}{2}g^{\mu\nu} \left\{ \partial_\mu \phi \partial_\nu \phi + \frac{1}{4}g^2(W_\mu^1 W_\nu^1 + W_\mu^2 W_\nu^2) \phi^2 + \frac{1}{4}(g^2 + g'^2)Z_\mu Z_\nu \phi^2 \right\} \quad (86)$$

contributes

$$T_{\mu\nu}(\phi) = \partial_\mu \phi \partial_\nu \phi + \frac{1}{4}g^2(W_\mu^1 W_\nu^1 + W_\mu^2 W_\nu^2) \phi^2 + \frac{1}{4}(g^2 + g'^2)Z_\mu Z_\nu \phi^2 - g_{\mu\nu}L(\phi) \quad (87)$$

The constant term is treated in the following section.

## 5. The $W^\pm$ and $Z^0$ Bosons

The coupling of  $W^\pm$  with the scalar field is described by the equations

$$\partial_\mu F^{\mu\nu}(W) + \frac{1}{4}g^2 W^\nu \phi^2 = 0 \quad (88)$$

$$\partial_\mu \partial^\mu \phi - \frac{1}{4}g^2 W_\mu W^\mu \phi = 0 \quad (89)$$

where  $\partial_\mu W^\mu = W^\mu \partial_\mu \phi = 0$ . These equations are identical to those of U(1), (14) and (15), with the replacement  $g \longrightarrow g/2$ . The solutions are polarized,  $W^\mu(u) = \epsilon^\mu \phi(u)$ , where

$$\phi(u) = \frac{2k_W}{g} \text{cn}(-k_\mu x^\mu) \quad (90)$$

Similarly, the coupling of  $Z^0$  is described by

$$\partial_\mu F^{\mu\nu}(Z) + \frac{1}{4}(g^2 + g'^2)Z^\nu \phi^2 = 0 \quad (91)$$

$$\partial_\mu \partial^\mu \phi - \frac{1}{4}(g^2 + g'^2)Z_\mu Z^\mu \phi = 0 \quad (92)$$

The solutions are  $Z^\mu(u) = \epsilon^\mu \phi(u)$ , where

$$\phi(u) = \frac{2k_Z}{\sqrt{g^2 + g'^2}} \text{cn}(-k_\mu x^\mu) \quad (93)$$

The calculations of  $T_{00}$  and  $T_{03}$  proceed as in the example of U(1). The replacement  $g \longrightarrow g/2$  is required for  $W^\pm$  and  $g \longrightarrow \sqrt{g^2 + g'^2}/2$

for  $Z^0$ . However, before integration can occur, the two factors  $k_W^2/g^2$  and  $k_Z^2/(g^2 + g'^2)$  must be eliminated. This is possible only if they are equal

$$\frac{k_W^2}{g^2} = \frac{k_Z^2}{g^2 + g'^2} \quad (94)$$

In this case, the volume element is uniquely defined (compare (45))

$$\frac{l^3}{V} dV = \frac{3\pi}{8K} \frac{g^2}{k_W^2 k^0 V} dV = \frac{3\pi}{8K} \frac{(g^2 + g'^2)}{k_Z^2 k^0 V} dV \quad (95)$$

Integration for  $W^\pm$  and  $Z^0$  may now go forward as in U(1).<sup>2</sup> The integrals for transverse and longitudinal fields all assume the form

$$E = \frac{l^3}{V} \int T_0^0 dV = \hbar\omega \quad (96)$$

$$cp^3 = \frac{l^3}{V} \int T_0^3 dV = \hbar c \frac{2\pi}{\lambda} \quad (97)$$

showing that the energy and momentum are conserved.

## 6. Concluding Remarks

The coupling theory is made tractable, with the choice of unitary gauge. This resembles the choice of Coulomb gauge in electrodynamics, in that the gauge invariance is no longer manifest. However, in the present case, the unitary gauge eliminates the scalar currents, leaving direct nonlinear coupling between the real scalar and vector fields. The equations of motion yield both transverse and longitudinal solutions, indicating the presence of mass.

In the U(1) model, scalar-vector coupling generates a single massive vector field, while in the electroweak theory there are two, the  $W^\pm$  and  $Z^0$ . They satisfy relation (94), yielding the mass ratio

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<sup>2</sup>Moreover, the constant terms are identical

$$\begin{aligned} T_{\mu\nu}(k^2) &= -\frac{4}{3} \frac{k_W^2}{g^2} (k_\mu k_\nu - \frac{1}{2} g_{\mu\nu} k^2) \\ &= -\frac{4}{3} \frac{k_Z^2}{g^2 + g'^2} (k_\mu k_\nu - \frac{1}{2} g_{\mu\nu} k^2) \end{aligned}$$

$$\frac{m_W}{m_Z} = \frac{k_W}{k_Z} = \frac{g}{\sqrt{g^2 + g'^2}} \quad (98)$$

Finally, the constant term in the energy tensor  $T_{\mu\nu}(k^2)$  has been introduced out of necessity. Without it, the energy and momentum would not satisfy the relation  $c^2\mathbf{p} = E\mathbf{v}$ , as they must; the work would simply be incomplete.

## Appendix A. Elliptic Functions [4, 5]

The elliptic functions  $\text{sn}(u, m)$ ,  $\text{cn}(u, m)$ , and  $\text{dn}(u, m)$  satisfy

$$\text{sn}^2(u, m) + \text{cn}^2(u, m) = 1 \quad (99)$$

$$\text{dn}(u, m) = \sqrt{1 - m \text{sn}^2(u, m)} \quad (100)$$

Their derivatives are

$$\frac{d \text{sn}(u, m)}{du} = \text{cn}(u, m) \text{dn}(u, m) \quad (101)$$

$$\frac{d \text{cn}(u, m)}{du} = -\text{sn}(u, m) \text{dn}(u, m) \quad (102)$$

$$\frac{d \text{dn}(u, m)}{du} = -m \text{sn}(u, m) \text{cn}(u, m) \quad (103)$$

In particular,

$$\begin{aligned} \frac{d^2 \text{cn}(u, m)}{du^2} &= -\text{cn}(u) \text{dn}^2(u) + m \text{sn}^2(u) \text{cn}(u) \\ &= (2m - 1) \text{cn}(u) - 2m \text{cn}^3(u) \end{aligned} \quad (104)$$

If the parameter  $m = \frac{1}{2}$ , then

$$\frac{d^2 \text{cn}(u, \frac{1}{2})}{du^2} = -\text{cn}^3(u, \frac{1}{2}) \quad (105)$$

Substitute  $\phi(u) = a \text{cn}(u, \frac{1}{2})$  into the differential equation

$$\frac{d^2 \phi(u)}{du^2} + \lambda \phi^3(u) = 0 \quad (106)$$

to find

$$-a \operatorname{cn}^3(u, \frac{1}{2}) + \lambda a^3 \operatorname{cn}^3(u, \frac{1}{2}) = 0 \quad (107)$$

The equation is satisfied if  $a^2 = 1/\lambda$

$$\phi(u) = \sqrt{\frac{1}{\lambda}} \operatorname{cn}(u, \frac{1}{2}) \quad (108)$$

The physical equation (23) yields

$$k_\mu k^\mu \frac{d^2 \phi(u)}{du^2} + g^2 \phi^3(u) = 0 \quad (109)$$

This equation is satisfied by (108) if  $\lambda = g^2/k^2$

$$\phi(u) = \frac{k}{g} \operatorname{cn}(-k_\mu x^\mu) \quad (110)$$

The elliptic functions, with  $m = \frac{1}{2}$ , satisfy two useful identities. The first is

$$\left(\frac{d \operatorname{cn}(u)}{du}\right)^2 = \operatorname{sn}^2(u) \operatorname{dn}^2(u) = \frac{1}{2} \{1 - \operatorname{cn}^4(u)\} \quad (111)$$

The second identity is

$$\frac{d}{du} \{\operatorname{sn}(u) \operatorname{cn}(u) \operatorname{dn}(u)\} = \frac{1}{2} \{3 \operatorname{cn}^4(u) - 1\} \quad (112)$$

and it follows that

$$\int \operatorname{cn}^4(u) du = \frac{u}{3} + \frac{2}{3} \operatorname{sn}(u) \operatorname{cn}(u) \operatorname{dn}(u) + \text{constant} \quad (113)$$

The period of the elliptic function is  $4K$ . (If  $m = \frac{1}{2}$ , then  $K \doteq 1.85$ .) Therefore, for motion along the  $x^3$ -axis

$$\operatorname{cn}(-k_\mu x^\mu) = \operatorname{cn}(k^3 x^3 - k^0 x^0) = \operatorname{cn} 4K \left( \frac{x^3}{\lambda} - \frac{t}{T} \right) \quad (114)$$

It follows that

$$ck^0 = \frac{4K}{T} = \frac{2K}{\pi} 2\pi f = \frac{2K}{\pi} \omega \quad (115)$$

$$k^3 = \frac{4K}{\lambda} = \frac{2K}{\pi} \frac{2\pi}{\lambda} \quad (116)$$

and

$$E = \hbar\omega = \frac{\pi}{2K} \hbar ck^0 \quad (117)$$

$$cp^3 = \hbar c \frac{2\pi}{\lambda} = \frac{\pi}{2K} \hbar ck^3 \quad (118)$$

## Appendix B. Scalar Lagrangian

### (a) Lagrangian

$$\begin{aligned} L(\Phi) &= g^{\mu\nu} (D_\mu \Phi)^\dagger (D_\nu \Phi) \\ &= \partial^\mu \phi^{+*} \partial_\mu \phi^+ + \partial^\mu \phi^{0*} \partial_\mu \phi^0 \\ &\quad + \left\{ [eA^\mu + \frac{1}{2}(g \cos \theta - g' \sin \theta) Z^\mu]^2 + \frac{1}{2} g^2 W^{+\mu} W_\mu^- \right\} \phi^{+*} \phi^+ \\ &\quad + [eA^\mu - g' \sin \theta Z^\mu] \left\{ \frac{g}{\sqrt{2}} W_\mu^+ \phi^{+*} \phi^0 + \frac{g}{\sqrt{2}} W_\mu^- \phi^{0*} \phi^+ \right\} \\ &\quad + \left\{ \frac{1}{2} g^2 W^{-\mu} W_\mu^+ + \frac{1}{4} (g^2 + g'^2) Z^\mu Z_\mu \right\} \phi^{0*} \phi^0 \\ &\quad - i [eA^\mu + \frac{1}{2} (g \cos \theta - g' \sin \theta) Z^\mu] (\phi^{+*} \partial_\mu \phi^+ - \partial_\mu \phi^{+*} \phi^+) \\ &\quad - \frac{i}{\sqrt{2}} g W^{-\mu} (\phi^{0*} \partial_\mu \phi^+ - \partial_\mu \phi^{0*} \phi^+) - \frac{i}{\sqrt{2}} g W^{+\mu} (\phi^{+*} \partial_\mu \phi^0 - \partial_\mu \phi^{+*} \phi^0) \\ &\quad + \frac{i}{2} \sqrt{g^2 + g'^2} Z^\mu (\phi^{0*} \partial_\mu \phi^0 - \partial_\mu \phi^{0*} \phi^0) \end{aligned} \quad (119)$$

### (b) Functional derivatives

$$\frac{\partial L}{\partial(\partial_\mu \phi^{0*})} = \partial^\mu \phi^0 + \frac{i}{\sqrt{2}} g W^{-\mu} \phi^+ - \frac{i}{2} \sqrt{g^2 + g'^2} Z^\mu \phi^0 \quad (120)$$

$$\begin{aligned} \frac{\partial L}{\partial \phi^{0*}} &= -\frac{i}{\sqrt{2}} g W^{-\mu} \partial_\mu \phi^+ + \frac{i}{2} \sqrt{g^2 + g'^2} Z^\mu \partial_\mu \phi^0 \\ &\quad + [eA^\mu - g' \sin \theta Z^\mu] \frac{1}{\sqrt{2}} g W_\mu^- \phi^+ \\ &\quad + \frac{1}{2} g^2 W^{-\mu} W_\mu^+ \phi^0 + \frac{1}{4} (g^2 + g'^2) Z^\mu Z_\mu \phi^0 \end{aligned} \quad (121)$$

and

$$\frac{\partial L}{\partial(\partial_\mu \phi^{+*})} = \partial^\mu \phi^+ + i [eA^\mu + \frac{1}{2} (g \cos \theta - g' \sin \theta) Z^\mu] \phi^+ + \frac{i}{\sqrt{2}} g W^{+\mu} \phi^0 \quad (122)$$

$$\begin{aligned}
\frac{\partial L}{\partial \phi^{+\ast}} = & -i[eA^\mu + \frac{1}{2}(g \cos \theta - g' \sin \theta)Z^\mu]\partial_\mu \phi^+ + \frac{1}{2}g^2 W^{+\mu} W_\mu^- \phi^+ \\
& + [eA^\mu + \frac{1}{2}(g \cos \theta - g' \sin \theta)Z^\mu]^2 \phi^+ \\
& + [eA^\mu - g' \sin \theta Z^\mu] \frac{1}{\sqrt{2}} g W_\mu^+ \phi^0 - \frac{i}{\sqrt{2}} g W^{+\mu} \partial_\mu \phi^0
\end{aligned} \tag{123}$$

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