

# Quantum Field Theory

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## 1 Derivation from the Standard Model

### 1.1 Electroweak Standard Model

Lagrangian with a global  $SU(2) \times U(1)$  symmetry:

$$L = i\bar{L}^{(l)}\gamma_\mu\partial^\mu L^{(l)} + i\bar{e}_R\gamma_\mu\partial^\mu e_R + \frac{1}{2}\partial_\mu\Phi^*\partial^\mu\Phi - m^2\Phi^*\Phi - \frac{1}{4}\lambda(\Phi^*\Phi)^2 - h_e\bar{L}^{(l)}\Phi e_R - \text{h.c.}$$

where  $l = e, \mu, \tau$  and  $a = 1, 2$ .

Local  $SU(2) \times U(1)$  symmetry:

This consists of two things. First changing the partial derivatives to covariant ones:

$$\partial^\mu \rightarrow D^\mu = \partial^\mu - \frac{i}{2}g\tau_k A_k^\mu - \frac{i}{2}g'YB^\mu$$

and second adding the kinetic terms

$$-\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

of the vector gauge particles to the lagrangian.

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g\epsilon^{abc}A_\mu^b A_\nu^c$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

$$\Phi = e^{\frac{i}{v}\pi^a(x)\tau^a} \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v + H(x)) \end{pmatrix}$$

This breaks the gauge invariance. The  $\partial^\mu\pi^a$  are going to be added to  $A_\mu^a$  so we can set  $\pi_a = 0$  now.

### 1.1.1 Higgs Terms

$$L_{Higgs} = \frac{1}{2} \partial_\mu \Phi^* \partial^\mu \Phi - m^2 \Phi^* \Phi - \frac{1}{4} \lambda (\Phi^* \Phi)^2$$

Plugging in the covariant derivatives and  $\Phi$  in U-gauge (symmetry breaking):

$$\begin{aligned} L_{Higgs} &= \frac{1}{2} \Phi^+ (\overleftarrow{\partial}_\mu + i g A_\mu^a \frac{\tau^a}{2} + i g' Y B_\mu) (\overrightarrow{\partial}^\mu + i g A^{a\mu} \frac{\tau^a}{2} + i g' Y B^\mu) \Phi - \lambda (\Phi^+ \Phi - \frac{v^2}{2})^2 = \\ &= \Phi_U^+ (\overleftarrow{\partial}_\mu + i g A_\mu^a \frac{\tau^a}{2} + i g' Y B_\mu) (\overrightarrow{\partial}^\mu + i g A^{a\mu} \frac{\tau^a}{2} + i g' Y B^\mu) \Phi_U - \lambda (\Phi_U^+ \Phi_U - \frac{v^2}{2})^2 = \\ &= \frac{1}{2} \partial_\mu H \partial^\mu H - \lambda v^2 H^2 - \lambda v H^3 - \frac{1}{4} \lambda H^4 + \\ &+ \frac{1}{8} (v+H)^2 \left( 2g^2 \frac{A_\mu^1 + i A_\mu^2}{\sqrt{2}} \frac{A^{1\mu} - i A^{2\mu}}{\sqrt{2}} + (g^2 + 4Y^2 g'^2) \frac{g A_\mu^3 - 2Y g' B_\mu}{\sqrt{g^2 + 4Y^2 g'^2}} \frac{g A^{3\mu} - 2Y g' B^\mu}{\sqrt{g^2 + 4Y^2 g'^2}} \right) = \\ &= \frac{1}{2} \partial_\mu H \partial^\mu H - \lambda v^2 H^2 - \lambda v H^3 - \frac{1}{4} \lambda H^4 + \frac{1}{8} (v+H)^2 (2g^2 W_\mu^- W^{+\mu} + (g^2 + 4Y^2 g'^2) Z_\mu Z^\mu) = \\ &= \frac{1}{2} \partial_\mu H \partial^\mu H - \lambda v^2 H^2 + \frac{1}{4} g^2 v^2 W_\mu^- W^{+\mu} + \frac{1}{8} (g^2 + 4Y^2 g'^2) Z_\mu Z^\mu - \lambda v H^3 - \frac{1}{4} \lambda H^4 + \\ &+ \frac{1}{2} v H g^2 W_\mu^- W^{+\mu} + \frac{1}{4} v H (g^2 + 4Y^2 g'^2) Z_\mu Z^\mu + \frac{1}{4} H^2 g^2 W_\mu^- W^{+\mu} + \frac{1}{8} H^2 (g^2 + 4Y^2 g'^2) Z_\mu Z^\mu \end{aligned}$$

Where we put

$$\begin{aligned} W_\mu^\pm &= \frac{1}{\sqrt{2}} (A_\mu^1 \mp i A_\mu^2) \\ Z_\mu &= \frac{g}{\sqrt{g^2 + 4Y^2 g'^2}} A_\mu^3 - \frac{2Y g'}{\sqrt{g^2 + 4Y^2 g'^2}} B_\mu \end{aligned}$$

Now we define  $\theta_W$  by the relation

$$\cos \theta_W = \frac{g}{\sqrt{g^2 + 4Y^2 g'^2}}$$

so that we can then write:

$$Z_\mu = \cos \theta_W A_\mu^3 - \sin \theta_W B_\mu$$

### 1.1.2 Yukawa terms

$$\begin{aligned} L_{Yukawa} &= -h_l \bar{L} \Phi e_R - \text{h.c.} = -h_l \bar{L} \Phi_U e_R - \text{h.c.} = \\ &= -\frac{1}{\sqrt{2}} h_l (v+H) (\bar{e}_L e_R + \bar{e}_R e_L) = -\frac{1}{\sqrt{2}} h_l (v+H) \bar{e} e = \\ &= -\frac{1}{\sqrt{2}} h_l v \bar{e} e - \frac{1}{\sqrt{2}} h_l \bar{e} e H \end{aligned}$$

## 1.2 QED

The QED Lagrangian density is

$$L = \bar{\psi}(ic\gamma^\mu D_\mu - mc^2)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

where

$$\psi = (\psi_1\psi_2\psi_3\psi_4)$$

and

$$D_\mu = \partial_\mu + ieA_\mu$$

is the gauge covariant derivative and ( $e$  is the elementary charge, which is 1 in atomic units)

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

is the electromagnetic field tensor. It's astonishing, that this simple Lagrangian can account for all phenomena from macroscopic scales down to something like  $10^{-13}$  cm. So of course Feynman, Schwinger and Tomonaga received the 1965 Nobel Prize in Physics for such a fantastic achievement.

Plugging this Lagrangian into the Euler-Lagrange equation of motion for a field, we get:

$$\begin{aligned}(ic\gamma^\mu D_\mu - mc^2)\psi &= 0 \\ \partial_\nu F^{\nu\mu} &= -ec\bar{\psi}\gamma^\mu\psi\end{aligned}$$

The first equation is the Dirac equation in the electromagnetic field and the second equation is a set of Maxwell equations ( $\partial_\nu F^{\nu\mu} = -ej^\mu$ ) with a source  $j^\mu = c\bar{\psi}\gamma^\mu\psi$ , which is a 4-current coming from the Dirac equation.

The fields  $\psi$  and  $A^\mu$  are quantized. The first approximation is that we take  $\psi$  as a wavefunction, that is, it is a classical 4-component field. It can be shown that this corresponds to taking three orders in the perturbation theory.

The first component  $A_0$  of the 4-potential is the electric potential, and because this is the potential that (as we show in a moment) is in the Schrödinger equation, we denote it by  $V$ :

$$A_\mu = \left(\frac{V}{ec}, A_1, A_2, A_3\right)$$

So in the non-relativistic limit, the  $\frac{V}{e}$  corresponds to the electric potential. We multiply the Dirac equation by  $\gamma^0$  from left to get:

$$\begin{aligned}0 &= \gamma^0(ic\gamma^\mu D_\mu - mc^2)\psi = \gamma^0(ic\gamma^0(\partial_0 + i\frac{V}{c}) + ic\gamma^i(\partial_i + ieA_i) - mc^2)\psi = \\ &= (ic\partial_0 + ic\gamma^0\gamma^i\partial_i - \gamma^0mc^2 - V - ce\gamma^0\gamma^iA_i)\psi\end{aligned}$$

and we make the following substitutions (it's just a formalism, nothing more):  $\beta = \gamma^0$ ,  $\alpha^i = \gamma^0\gamma^i$ ,  $p_j = -i\partial_j$ ,  $\partial_0 = \frac{1}{c}\frac{\partial}{\partial t}$  to get

$$(i\frac{\partial}{\partial t} - c\alpha^ip_i - \beta mc^2 - V - ce\alpha^iA_i)\psi = 0.$$

This, in most solid state physics texts, is usually written as

$$i\frac{\partial\psi}{\partial t} = H\psi,$$

where the Hamiltonian is given by

$$H = c\alpha^i(p_i + eA_i) + \beta mc^2 + V.$$

The right hand side of the Maxwell equations is the 4-current, so it's given by:

$$j^\mu = c\bar{\psi}\gamma^\mu\psi$$

Now we make the substitution  $\psi = e^{-imc^2 t}\varphi$ , which states, that we separate the largest oscillations of the wavefunction and we get

$$j^0 = c\bar{\psi}\gamma^0\psi = c\psi^\dagger\psi = c\varphi^\dagger\varphi$$

$$j^i = c\bar{\psi}\gamma^i\psi = c\psi^\dagger\alpha^i\psi = c\varphi^\dagger\alpha^i\varphi$$

The Dirac equation implies the Klein-Gordon equation:

$$\begin{aligned} (-ic\gamma^\mu D_\mu - mc^2)(ic\gamma^\nu D_\nu - mc^2)\psi &= (c^2\gamma^\mu\gamma^\nu D_\mu D_\nu + m^2c^4)\psi = \\ &= (c^2 D^\mu D_\mu - ic^2[\gamma^\mu, \gamma^\nu]D_\mu D_\nu + m^2c^4)\psi = 0 \end{aligned}$$

Note however, the  $\psi$  in the true Klein-Gordon equation is just a scalar, but here we get a 4-component spinor. Now:

$$\begin{aligned} D_\mu D_\nu &= (\partial_\mu + ieA_\mu)(\partial_\nu + ieA_\nu) = \partial_\mu\partial_\nu + ie(A_\mu\partial_\nu + A_\nu\partial_\mu + (\partial_\mu A_\nu)) - e^2 A_\mu A_\nu \\ [D_\mu, D_\nu] &= D_\mu D_\nu - D_\nu D_\mu = ie(\partial_\mu A_\nu) - ie(\partial_\nu A_\mu) \end{aligned}$$

We rewrite  $D^\mu D_\mu$ :

$$\begin{aligned} D^\mu D_\mu &= g^{\mu\nu} D_\mu D_\nu = \partial^\mu\partial_\mu + ie((\partial^\mu A_\mu) + 2A^\mu\partial_\mu) - e^2 A^\mu A_\mu = \\ &= \partial^\mu\partial_\mu + ie((\partial^0 A_0) + 2A^0\partial_0 + (\partial^i A_i) + 2A^i\partial_i) - e^2(A^0 A_0 + A^i A_i) = \\ &= \partial^\mu\partial_\mu + i\frac{1}{c^2}\frac{\partial V}{\partial t} + 2i\frac{V}{c^2}\frac{\partial}{\partial t} + ie(\partial^i A_i) + 2ieA^i\partial_i - \frac{V^2}{c^2} - e^2 A^i A_i \end{aligned}$$

We use the identity  $\frac{\partial}{\partial t}\left(e^{-imc^2 t}f(t)\right) = e^{-imc^2 t}(-imc^2 + \frac{\partial}{\partial t})f(t)$  to get:

$$\begin{aligned} L &= c^2\partial^\mu\psi^*\partial_\mu\psi - m^2c^4\psi^*\psi = \frac{\partial}{\partial t}\psi^*\frac{\partial}{\partial t}\psi - c^2\partial^i\psi^*\partial_i\psi - m^2c^4\psi^*\psi = \\ &= (imc^2 + \frac{\partial}{\partial t})\varphi^*(-imc^2 + \frac{\partial}{\partial t})\varphi - c^2\partial^i\varphi^*\partial_i\varphi - m^2c^4\varphi^*\varphi = \\ &= 2mc^2\left[\frac{1}{2}i(\varphi^*\frac{\partial\varphi}{\partial t} - \varphi\frac{\partial\varphi^*}{\partial t}) - \frac{1}{2m}\partial^i\varphi^*\partial_i\varphi + \frac{1}{2mc^2}\frac{\partial\varphi^*}{\partial t}\frac{\partial\varphi}{\partial t}\right] \end{aligned}$$

The constant factor  $2mc^2$  in front of the Lagrangian is of course irrelevant, so we drop it and then we take the limit  $c \rightarrow \infty$  (neglecting the last term) and we get

$$L = \frac{1}{2}i(\varphi^* \frac{\partial \varphi}{\partial t} - \varphi \frac{\partial \varphi^*}{\partial t}) - \frac{1}{2m} \partial^i \varphi^* \partial_i \varphi$$

After integration by parts we arrive at

$$L = i\varphi^* \frac{\partial \varphi}{\partial t} - \frac{1}{2m} \partial^i \varphi^* \partial_i \varphi$$

The nonrelativistic limit can also be applied directly to the Klein-Gordon equation:

$$\begin{aligned} 0 &= (c^2 D^\mu D_\mu + m^2 c^4) \psi = \\ &= \left( c^2 \partial^\mu \partial_\mu + i \frac{\partial V}{\partial t} + 2iV \frac{\partial}{\partial t} + iec^2 (\partial^i A_i) + 2iec^2 A^i \partial_i - V^2 - e^2 c^2 A^i A_i + m^2 c^4 \right) e^{-imc^2 t} \varphi = \\ &= \left( \frac{\partial^2}{\partial t^2} - c^2 \nabla^2 + 2iV \frac{\partial}{\partial t} + i \frac{\partial V}{\partial t} + iec^2 (\partial^i A_i) + 2iec^2 A^i \partial_i - V^2 - e^2 c^2 A^i A_i + m^2 c^4 \right) e^{-imc^2 t} \varphi = \\ &= e^{-imc^2 t} \left( (-imc^2 + \frac{\partial}{\partial t})^2 - c^2 \nabla^2 + 2iV(-imc^2 + \frac{\partial}{\partial t}) + i \frac{\partial V}{\partial t} + iec^2 (\partial^i A_i) + 2iec^2 A^i \partial_i - V^2 + \right. \\ &\quad \left. - e^2 c^2 A^i A_i + m^2 c^4 \right) \varphi = \\ &= e^{-imc^2 t} \left( -2imc^2 \frac{\partial}{\partial t} + \frac{\partial^2}{\partial t^2} - c^2 \nabla^2 + 2Vmc^2 + 2iV \frac{\partial}{\partial t} + i \frac{\partial V}{\partial t} + iec^2 (\partial^i A_i) + 2iec^2 A^i \partial_i - V^2 + \right. \\ &\quad \left. - e^2 c^2 A^i A_i \right) \varphi = \\ &= -2mc^2 e^{-imc^2 t} \left( i \frac{\partial}{\partial t} + \frac{\nabla^2}{2m} - V - \frac{1}{2mc^2} \frac{\partial^2}{\partial t^2} - \frac{i}{2mc^2} \frac{\partial V}{\partial t} + \frac{V^2}{2mc^2} - \frac{iV}{mc^2} \frac{\partial}{\partial t} + \right. \\ &\quad \left. - \frac{ie}{2m} \partial^i A_i - \frac{ie}{m} A^i \partial_i + \frac{e^2}{2m} A^i A_i \right) \varphi \end{aligned}$$

Taking the limit  $c \rightarrow \infty$  we again recover the Schrödinger equation:

$$i \frac{\partial}{\partial t} \varphi = \left( -\frac{\nabla^2}{2m} + V + \frac{ie}{2m} \partial^i A_i + \frac{ie}{m} A^i \partial_i - \frac{e^2}{2m} A^i A_i \right) \varphi,$$

we rewrite the right hand side a little bit:

$$\begin{aligned} i \frac{\partial}{\partial t} \varphi &= \left( \frac{1}{2m} (\partial^i \partial_i + ie \partial^i A_i + 2ie A^i \partial_i - e^2 A^i A_i) + V \right) \varphi, \\ i \frac{\partial}{\partial t} \varphi &= \left( \frac{1}{2m} (\partial^i + ie A^i) (\partial_i + ie A_i) + V \right) \varphi, \end{aligned}$$

And we get the usual form of the Schrödinger equation for the vector potential  $\mathbf{A} = (A_1, A_2, A_3)$ :

$$i \frac{\partial}{\partial t} \varphi = \left( -\frac{(\nabla + ie \mathbf{A})^2}{2m} + V \right) \varphi.$$