

Notes on Quantum Field Theory

Yehyun Choi

August 2024

Contents

1	Scalar Field Theory	2
1.1	Motivation, Causality	2
1.2	Formulation	2
1.3	Symmetries and Conservation Laws	3
1.4	Complex Scalar Fields	4
2	Spin 1/2 Field Theory	5
2.1	Groups	5
2.2	Representations	5
2.3	Weyl Formalism	7
2.4	Dirac Theory	8
2.5	Discrete Symmetries	9
3	Interacting Fields	10
3.1	Formulation	10
3.2	Feynman Diagrams	12
3.3	Scattering	13
3.4	ϕ^3 Theory	14
3.5	ϕ^4 Theory	14
3.6	Yukawa Theory	14
3.7	Quantum Electrodynamics	14
4	Formal Developments	15
4.1	Optical Theorem	15
4.2	Renormalization	15
4.3	Regularization	16
4.4	Loop Integrals	16
5	Path Integral Formulation	17
5.1	Derivation	17
5.2	Quantization of Scalar Fields	17
5.3	Quantization of EM Field	18

1 Scalar Field Theory

1.1 Motivation, Causality

Lec 1, P&S 2.1

The field viewpoint is needed because quantum mechanics breaks causality. This can be shown from:

1. Explicitly calculating the propagator between \mathbf{x} and \mathbf{x}_0 . For rational function of x and t , $U(t) \sim e^{-m\sqrt{x^2-t^2}}$ with no cutoff¹.
2. Recalling that all Hermitian operators are observable; in relativity, this cannot be true because 2 spatially separated observables cannot affect each other. In other words, $[O_1, O_2] \neq 0$ for spatially separated O_1, O_2 .

With Lorentz transformations, we can prove that QFT is **causal** - in other words, if $(x-y)^2 < 0$, then $[O(x), O(y)] = 0$, or spacelike operators commute. To see this, we let $\phi(x) = \phi^-(x) + \phi^+(x)$, where each term corresponds to the creation and annihilation terms;

$$\phi^-(x) = \int \frac{d^3k}{\sqrt{(2\pi)^3 2\omega_k}} a_k e^{-ik \cdot x}, \quad \phi^+(x) = \int \frac{d^3k}{\sqrt{(2\pi)^3 2\omega_k}} a_k^\dagger e^{ik \cdot x}.$$

Then we can rewrite the commutator as

$$\begin{aligned} [\phi(x), \phi(y)] &= [\phi^-(x) + \phi^+(x), \phi^-(y) + \phi^+(y)] = [\phi^-(x), \phi^+(y)] + [\phi^+(x), \phi^-(y)] \\ &= \phi^-(x)\phi^+(y) - \phi^-(y)\phi^+(x). \end{aligned}$$

However, $\phi^-(x)\phi^+(y) = \phi^-(y)\phi^+(x)$ if $(x-y)^2 < 0$, because there's a proper Lorentz transformation between $x-y$ and $y-x$. One could think that causality is restored as the amplitude of the particle propagating from y to x is exactly canceled out by the antiparticle propagating from x to y .

1.2 Formulation

Lec 2, 3, 4, 5

In QFT, observables are operator valued fields. We start with scalar fields - fields that are invariant under Lorentz transformations; $\phi'(x') = \phi(x)$, where $x' = \Lambda x$.

We start by requiring that the action is

1. Lorentz invariant;
2. Causal - S is local, $S = \int d^4x L(\phi, \partial_\mu \phi)$, with $\phi(x)$ only, no $\phi(y)$;
3. Corresponding to EoM with 2nd order in time derivative - only possible terms are ϕ^2 and $(\partial_\mu \phi)^2$ (note that higher order time derivatives would be one higher in length scale, $L \sim 10^{-35}$ m.)

This is sufficient to write down the general form of the action:

$$S = \int d^4x \left(\frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{m^2}{2} \phi^2 \right).$$

From the Euler-Lagrange equation,

$$\frac{\partial \mathcal{L}}{\partial \phi} - \partial_\mu \left(\frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi)} \right) = 0 \implies \partial_\mu \partial^\mu \phi + m^2 \phi = 0.$$

This is known as the Klein-Gordon equation.

To solve the Klein-Gordon equation, we can try

$$\phi(\mathbf{x}, t) = \int \frac{d^3k}{(2\pi)^{3/2}} e^{i\mathbf{k} \cdot \mathbf{x}} \tilde{\phi}(\mathbf{k}, t) \implies \frac{\partial^2 \tilde{\phi}}{\partial t^2} + \omega_k^2 \tilde{\phi} = 0,$$

where $\omega_k^2 = k^2 + m^2$. Further imposing the realness conditions, we have $\tilde{\phi}(\mathbf{k}, t) = \tilde{\phi}^*(-\mathbf{k}, t)$, giving us

$$\phi(\mathbf{x}, t) = \int \frac{d^3k}{\sqrt{(2\pi)^3 \cdot 2\omega_k}} (a_k e^{-ik \cdot x} + a_k^* e^{ik \cdot x}), \quad (1.1)$$

where we have defined $k^\mu = (\omega_k, \mathbf{k})$ and $x^\mu = (t, \mathbf{x})$. Note that the factors of $\sqrt{2\omega_k}$ and a_k, a_k^* are constants chosen for convention - this is called Harmonic normalization (this normalizes $\langle \mathbf{p} | \mathbf{q} \rangle$). Note that $\delta(\mathbf{p})$ has units \mathbf{p}^{-1} so it's not Lorentz invariant)

For full quantization, we obtain $\pi(x)$, the canonical momentum field, as $\partial_\phi \mathcal{L} = \pi$. For the Klein-Gordon theory,

$$\pi(\mathbf{x}, t) = \frac{\partial \mathcal{L}}{\partial \dot{\phi}} = \int \frac{d^3k}{\sqrt{(2\pi)^3 \cdot 2\omega_k}} \left(a_k (-i\omega_k) e^{-ik \cdot x} + a_k^\dagger (i\omega_k) e^{ik \cdot x} \right). \quad (1.2)$$

Imposing the canonical commutation relations² (add stuff):

$$[\phi(\mathbf{x}, t), \phi(\mathbf{y}, t)] = 0, \quad [\pi(\mathbf{x}, t), \pi(\mathbf{y}, t)] = 0, \quad [\phi(\mathbf{x}, t), \pi(\mathbf{y}, t)] = i\delta(\mathbf{x} - \mathbf{y}), \quad (1.3)$$

we solve for the ladder operators³

$$a_k = i \int \frac{d^3x}{\sqrt{(2\pi)^3 \cdot 2\omega_k}} \cdot e^{ik \cdot x} \left[\dot{\phi}(x) - i\omega_k \phi(x) \right], \quad a_k^\dagger = -i \int \frac{d^3x}{\sqrt{(2\pi)^3 \cdot 2\omega_k}} \cdot e^{-ik \cdot x} \left[\dot{\phi}(x) + i\omega_k \phi(x) \right].$$

¹<https://physics.stackexchange.com/a/105049>

²<https://physics.stackexchange.com/a/573940>

³<https://physics.stackexchange.com/q/304539>

We see that the ladder operators

$$[a_k, a_k^\dagger] = \delta(\mathbf{k} - \mathbf{k}'). \quad (1.4)$$

With the conjugate momentum defined, we can write the Hamiltonian:

$$H = \int d^3x \left[\frac{1}{2} \pi^2 + \frac{1}{2} (\nabla \phi)^2 + \frac{m^2}{2} \phi^2 \right] = \int d^3k \cdot \frac{1}{2} \omega_k (a_k a_k^\dagger + a_k^\dagger a_k).$$

Note that $a_k a_k^\dagger = \delta(0)$ blows up. This, analogous to summing the vacuum energy density over all space and modes, is known as the cosmological constant⁴ and can be canceled in the absence of gravity. This operation of canceling out the vacuum energy is called the **normal ordering** - when acted on a product of annihilation and creation operators, all the creation operators come to the front - for example, $:aa^\dagger := a^\dagger a$, and so on.

The space of states in QFT is called the Fock space. The particle states $|k\rangle = a_k^\dagger |0\rangle$ are orthonormal and complete:

$$\langle \mathbf{k}' | \mathbf{k} \rangle = \delta(\mathbf{k} - \mathbf{k}'), \quad \mathbb{1} = \int \frac{d^3k}{(2\pi)^3 2\omega_k} |\mathbf{k}\rangle \langle \mathbf{k}|.$$

Addendum about translation operator, Lec. 4

Lorentz transformations The Lorentz transformations have a unitary representation $U(\Lambda) |k\rangle = |\Lambda k\rangle$ in the relativistic normalization of states - that is, there exists $U(\Lambda)$ such that $U(\Lambda_1)U(\Lambda_2) = U(\Lambda_1\Lambda_2)$ and $U^\dagger U = \mathbb{1}$. We see that the following conditions are satisfied:

1. Representation condition: $U(\Lambda_1)(\Lambda_2) |k\rangle = U(\Lambda_1\Lambda_2) |k\rangle$, follows from the definition;
2. Unitarity: First, note that relativistic integrand is Lorentz invariant, as $\frac{d^3k}{(2\pi)^3 2\omega_k} = d^4k \delta(k^2 - m^2)$. Then, from the completeness relation,

$$UU^\dagger = \int \frac{d^3k}{(2\pi)^3 2\omega_k} |\Lambda k\rangle \langle \Lambda k| = \int \frac{d^3k'}{(2\pi)^3 2\omega_{k'}} |k'\rangle \langle k'| = \mathbb{1},$$

where $k' = \Lambda k$.

Note that relativistic creation/annihilation operators and field operators follow

$$\alpha^\dagger(\Lambda k) = U(\Lambda) \alpha_k^\dagger U(\Lambda)^{-1}, \quad U \phi U^\dagger = \phi(\Lambda x).$$

In other words, $\phi(x)$ transforms like a scalar.

1.3 Symmetries and Conservation Laws

1.3.1 Continuous Symmetries

Lec 6,

As far as symmetries and conservation laws are concerned, we note that

1. Symmetries have unitary representations⁵; for $U(R)$ corresponding to rotation R , $U(R_1)U(R_2) = U(R_1R_2)$ and $U^\dagger U = \mathbb{1}$.
2. Symmetries should leave the dynamics unchanged; for $|\psi\rangle = U |\phi\rangle$, $e^{-iHt} |\psi\rangle = U e^{-iHt} |\phi\rangle \implies U^\dagger H U = H$.

For a continuous symmetry, we can also write $R \sim \mathbb{1} + i\epsilon T$, where T is the infinitesimal generator of symmetry. We can also relate infinitesimal symmetry to a discrete one by exponentiating - $R = e^{i\epsilon T}$. The generators are a Lie algebra, closed under the Lie bracket; $[T^a, T^b] = i f^{abc} T^c$, where f^{abc} is the structure constant; in $SO(3)$, this is the Levi-Civita symbol. The generators for a unitary transformation are called charge operator:

$$U(\mathbb{1} + i\epsilon T) = 1 + i\epsilon Q, \quad U^{-1} = U^\dagger \implies Q = Q^\dagger.$$

Further imposing the dynamics condition, we have $[Q, H] = 0$.

Furthermore, the finite transformations $R = e^{i\epsilon T}$ form a Lie group - they are related to Lie algebra by the BCH formula. Lie groups are also closed under (matrix) multiplication; $R(h)R(g) = R(h \circ g) \implies e^{i\epsilon T^a} e^{i\epsilon T^b} = e^{i\epsilon T^c}$.

1.3.2 Conservation Laws

Recall that if the Lagrangian changes by a total derivative, the action doesn't change. Explicitly, we have

$$\delta \mathcal{L} = \frac{\partial \mathcal{L}}{\partial \phi_a} \delta \phi^a + \frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi^a)} \partial_\mu \delta \phi^a = \partial_\mu F^\mu \implies \partial_\mu \left(\frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi^a)} \delta \phi^a - F^\mu \right) \equiv \partial_\mu J^\mu = 0.$$

We define J^μ to be the **Noether current**. The corresponding conserved charge can be found $Q = \int d^3x J^0$.

As an example, we look at **translational symmetries**. If the action has no explicit x dependency, we can vary the fields

$$\phi^a(x^\mu + \epsilon a^\mu) \sim \phi^a(x^\mu) + \epsilon a^\mu \partial_\mu \phi^a, \quad \mathcal{L}(x^\mu + \epsilon a^\mu) \sim \mathcal{L}(x) + \epsilon a^\mu \partial_\mu \mathcal{L}.$$

Hence, $\delta \phi^a = a^\mu \partial_\mu \phi^a$, and $F^\mu = a^\mu \mathcal{L}$. The corresponding Noether current can be found to be

$$J^\nu = \frac{\partial \mathcal{L}}{\partial (\partial_\nu \phi^a)} \delta \phi^a - F^\nu = \frac{\partial \mathcal{L}}{\partial (\partial_\nu \phi^a)} a^\mu \partial_\mu \phi^a - a^\nu \mathcal{L} = a^\mu T_\mu^\nu, \quad T_\nu^\mu = \frac{\partial \mathcal{L}}{\partial (\partial_\nu \phi)} \partial_\mu \phi - \delta_\nu^\mu \mathcal{L}.$$

We define T_ν^μ to be the **stress-energy tensor**. From $\partial_\nu J^\nu = 0$, it holds that $\partial_\nu T_\nu^\mu = 0$ as well. The conserved charge, or the 4-momentum in this case, can be found

$$\int d^3x T^{\mu 0} = p^\mu, \quad \partial_t p^\mu = 0.$$

As an example, for a real scalar field,

$$: H := \int d^3k \cdot \omega_k a_k^\dagger a_k, \quad : p^\mu := \int d^3k \cdot k^\mu a_k^\dagger a_k.$$

⁴Turns out, the observed cosmological constant is 10^{-120} times smaller - this is known as the cosmological constant/fine tuning problem.

⁵Stated by Wigner's theorem.

1.3.3 Discrete Symmetries

2nd half Lec 7

There also exists discrete symmetries associated with Lorentz transformations, defined $\Lambda^\top g \Lambda = g$. The first is the **parity reversal**, defined, for a scalar field, as a unitary, linear operator that satisfies

$$U_p : \phi(t, \mathbf{x}) \mapsto \phi(t, -\mathbf{x}) \implies U_p : a_k, a_k^\dagger \mapsto a_{-k}, a_{-k}^\dagger$$

where we let $\mathbf{k} \rightarrow -\mathbf{k}$ in the field integral.

Next, we have the **time reversal**, defined as a unitary, anti-linear operator that satisfies

$$U_t : \phi(t, \mathbf{x}) \mapsto \phi^*(-t, \mathbf{x}) \implies U_t : a_k, a_k^\dagger \mapsto a_{-k}, a_{-k}^\dagger,$$

where $k \sim \hat{x} \rightarrow -k$ and $i \rightarrow -i$ in this transformation.

Lastly, the **charge conjugation** is a unitary operator, defined for complex fields, that satisfies

$$U_c : \psi(t, \mathbf{x}) \mapsto \psi^\dagger(t, \mathbf{x}), \quad U_c : b_k, b_k^\dagger \mapsto c_k, c_k^\dagger.$$

For non-interacting theories, all combinations of C, P, and T are symmetries. However, for interacting theories, C, P, and CP can be broken, but never **CPT**.

1.4 Complex Scalar Fields

1st half Lec 7,

While we have found symmetries with x -dependence so far, another group of symmetries, called **internal symmetries** exist. As a motivation, consider a system consisting of two real (independent), identical scalar fields:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi^1)^2 + \frac{1}{2}(\partial_\mu \phi^2)^2 - \frac{1}{2}m_1^2 \phi_1^2 - \frac{1}{2}m_2^2 \phi_2^2.$$

It is possible to “rotate” - $U(1) \sim SO(2)$ symmetry two fields into each other: $\begin{pmatrix} \phi^1 \\ \phi^2 \end{pmatrix} \rightarrow \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \phi^1 \\ \phi^2 \end{pmatrix}$. The current and charge associated with this symmetry is

$$J^\mu = (\partial^\mu \phi^1) \phi^2 - (\partial^\mu \phi^2) \phi^1, \quad Q = -i \int d^3k (a_k^{2\dagger} a_k^1 - a_k^{1\dagger} a_k^2).$$

Because $[H, Q] = 0$, it is possible to diagonalize the charge operator; let

$$b_k = \frac{1}{\sqrt{2}}(a_k^1 + ia_k^2), \quad c_k = \frac{1}{\sqrt{2}}(a_k^1 - ia_k^2).$$

whThe commutation relations still hold:

$$[b, b] = [c, c] = [b, c^\dagger] = 0,$$

and each operator corresponds to creating/annihilating a $+1$ charge (b, b^\dagger) or a -1 charge (c, c^\dagger) particle.

With these new definitions, we can write

$$Q = \int d^3k (b_k^\dagger b_k - c_k^\dagger c_k), \quad H := \int d^3k \cdot \omega_k (b_k^\dagger b_k + c_k^\dagger c_k).$$

Furthermore, we can define the field operator as

$$\psi = \frac{1}{\sqrt{2}}(\phi^1 + i\phi^2), \quad \psi = \int \frac{d^3k}{\sqrt{(2\pi)^3 2\omega_k}} (b_k e^{ik \cdot x} + c_k^\dagger e^{-ik \cdot x}), \quad \psi^\dagger = \int \frac{d^3k}{\sqrt{(2\pi)^3 2\omega_k}} (b_k^\dagger e^{-ik \cdot x} + c_k e^{ik \cdot x}),$$

with commutation relations

$$[\psi, \psi] = [\psi^\dagger, \psi^\dagger] = 0, \quad [\psi(x, t), \dot{\psi}^\dagger(y, t)] = i\delta(x - y).$$

The ψ field creates an anti-particle (c^\dagger) and annihilates particle (b), and the opposite for $\tilde{\psi}$.

As a side note, when written as a complex scalar, the “rotation internal symmetry” becomes a simple phase factor - they are $SO(2) \sim U(1)$ symmetries - $R\psi = \psi e^{-i\theta}$, where R is the motivating rotation matrix.

We can write the Lagrangian density and the rotation symmetry:

$$\mathcal{L} = \partial_\mu \psi^\dagger \partial^\mu \psi - m^2 \psi^\dagger \psi, \quad J_\mu = i [\psi \partial_\mu \psi^\dagger - \psi^\dagger \partial_\mu \psi].$$

2 Spin 1/2 Field Theory

2.1 Groups

Lec 22

The **Poincare group** $P = \{(\Lambda, a)\}$ with multiplication $(\Lambda_1, a_1) \cdot (\Lambda_2, a_2) = (\Lambda_1 \Lambda_2, \Lambda_1 a_2 + a_1)$ is the group of isometry transformations (Lorentz + translations, $x' = \Lambda x + a$) of the Minkowski spacetime.

The basic subgroups include homogeneous Lorentz group $L = \{(\Lambda, 0)\}$ and translations $T_4 = \{(\mathbb{1}, a)\}$.

The **Lorentz Group** $\{\Lambda\}$ is a matrix group defined $\Lambda^\top g \Lambda = g$, where g is the Minkowski $+, -, -, -$ metric. The generators can be written

$$\Lambda^\top g \Lambda = (\mathbb{1} - \omega^\top) g (\mathbb{1} - \omega) = g \implies \omega g = -g \omega^\top, \quad \omega^{\mu\nu} = -\omega^{\nu\mu}.$$

From antisymmetry, there are 6 real parameters over $\mu\nu$. Per convention, the generators ω are typically written

$$-\omega = \frac{i}{2} \omega^{\mu\nu} S_{\mu\nu},$$

where $S_{\mu\nu}$ are fixed matrices. Its lie algebra is

$$[S_{\mu\nu}, S_{\omega\rho}] = -i(g_{\mu\omega} S_{\nu\rho} + g_{\nu\rho} S_{\mu\omega} - g_{\mu\rho} S_{\nu\omega} - g_{\nu\omega} S_{\mu\rho}).$$

For example, the fundamental/vector $(1/2, 1/2)$ representation of $S_{\mu\nu}$ is

$$(S_{\mu\nu})^{\lambda\rho} = i(\delta_\mu^\lambda \delta_\nu^\rho - \delta_\nu^\lambda \delta_\mu^\rho).$$

If we define

- $S^{0i} = -S^{i0} = K^i$ generator of boost, $\omega^{i0} = -\omega^{0i}$ rapidity;
- $S^{ik} = \epsilon^{ikl} J^l$ generator of rotation, $\omega^{ik} = \epsilon^{ikl} \omega^l$ rotation angle,

then

$$[J^i, J^k] = i\epsilon^{ikl} J_l, \quad [J^i, K^i] = i\epsilon^{ikl} K_l, \quad [K^i, K^l] = i\epsilon^{ikl} J_l.$$

Note that $\{K\}$ isn't a subgroup.

Lastly, because representation preserves structure, we can simply take the matrix exponential to get the finite transformations:

$$\Lambda = \exp\left(\frac{i}{2} \omega^{\mu\nu} S_{\mu\nu}\right) = \exp(i(\omega \cdot \mathbf{J} + \omega u \cdot \mathbf{K})).$$

2.2 Representations

Lec 23-25

First, we introduce fields and states:

- **Fields** are operators on Hilbert space. They are finite dimensional representations of the Lorentz group - the position is already the argument of the field - and transform per the Poincare group. We write

$$U(\Lambda, a) \circ \phi_\alpha(x) \circ U^{-1}(\Lambda, a) = D_{\alpha\beta} \phi_\beta(\Lambda x + a).$$

$D_{\alpha\beta}$ is the Lorentz transformation matrix, which isn't necessarily unitary.

- **States** are vectors in Hilbert space. They are representations of the Poincare group - since the Casimir elements have eigenvalues that describe the mass and spin - and transform per the Lorentz group (states don't depend on the position) Therefore, we simply write

$$\Lambda : |k\rangle \rightarrow U(\Lambda) |k\rangle.$$

2.2.1 Representations of the Poincare Group

We use Wigner's classification on irreducible representations of the Poincare group. Given a state's momentum, we can find orbit \hat{p} for which there exists $L(p)$ such that $L(p) |\hat{p}\rangle = |p\rangle$. The little group denotes the isometry group of \hat{p} (formally defined $\{\Lambda\}$ such that $\Lambda \hat{p} = \hat{p}$.)

Orbit/characteristic momentum	\hat{p}	Little group $H\hat{p}$
$p^2 = m^2, p^2 > 0$	$(m, 0)$	$\text{SO}(3) \sim \text{SU}(2)$
$p^2 = 0, p^0 > 0$	$(1, \hat{e}_3)$	E_2
$p = 0$	$(0, 0)$	$L_+^\uparrow \sim \text{SL}(2, \mathbb{C})$
$p^2 = -m^2$	$(0, m\hat{e}_3)$	$\text{SU}(1, 1)$

Now, we define the representation of $H\hat{p}$ as

$$U(\Lambda) |\hat{p}, \alpha\rangle = D_{\alpha\alpha'}(\Lambda) |\hat{p}, \alpha'\rangle, \quad \Lambda \in H\hat{p}.$$

Given the representation of $H\hat{p}$, we can find the representation of the general $\Lambda \notin H\hat{p}$ as well. Given $|p, \alpha\rangle \equiv U(L(p)) |\hat{p}, \alpha\rangle$,

$$\begin{aligned} U(\Lambda) |p, \alpha\rangle &= [U(L(\Lambda p)) U(L^{-1}(\Lambda p))] U(\Lambda) U(L(p)) |\hat{p}, \alpha\rangle \\ &= U(L(\Lambda p)) [U(L^{-1}(\Lambda p)) U(\Lambda) U(L(p))] |\hat{p}, \alpha\rangle \\ &= U(L(\Lambda p)) D_{\alpha\alpha'}(L^{-1}(\Lambda p) \Lambda L(p)) |\hat{p}, \alpha\rangle \\ &= D_{\alpha\alpha'}(L^{-1}(\Lambda p) \Lambda L(p)) |p, \alpha'\rangle. \end{aligned}$$

We have used the fact that $U(L^{-1}(\Lambda p)) U(\Lambda) U(L(p))$ is a representation of the little group and $D_{\alpha\alpha'}$ is a matrix.

Case 1 - $\hat{p} = (m, 0)$, $H\hat{p} = \mathbf{SO}(3) \sim \mathbf{SU}(2)$ The $\mathbf{SU}(2)$ group can be represented by the particle's J^2 and J_3 values. We let $|\hat{p}, \alpha\rangle \rightarrow |\hat{p}, j\sigma\rangle$, where j is total spin and σ is the third component. The D matrix is written

$$U(\Lambda) |p, j\sigma\rangle = D_{\sigma\sigma'}^j(L^{-1}(\Lambda p)\Lambda L(p)) |\Lambda p, j\sigma'\rangle.$$

For moving particles, $[J^i, p^k] = i\epsilon^{ikl}p^l \neq 0$, which necessitates the helicity, defined

$$\Sigma = \frac{\mathbf{J} \cdot \mathbf{p}}{|\mathbf{p}|} \implies [p^i, \Sigma] = [p^i, J^k] \frac{p^k}{|\mathbf{p}|} = 0.$$

Therefore, for moving particles, we write $|p, j\sigma\rangle \rightarrow |p, j\lambda\rangle$ with $\Sigma |p, j\lambda\rangle = \lambda |p, j\lambda\rangle$.

Case 2 - $\hat{p} = (1, \hat{e}_3)$, $H\hat{p} = E_2$ The E_2 group can be written

$$\Lambda\hat{p} = \hat{p} \implies \omega\hat{p} = 0, \quad \begin{pmatrix} 0 & u^1 & u^2 & u^3 \\ -u^1 & 0 & \omega^{12} & \omega^{13} \\ -u^2 & -\omega^{12} & 0 & \omega^{23} \\ -u^3 & -\omega^{13} & -\omega^{23} & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} u_3 \\ -u_1 + \omega^{13} \\ -u_2 + \omega^{23} \\ -u_3 \end{pmatrix}.$$

Therefore there are only three generators, $J_3, J_1 + K_2, J_2 - K_1$. If we let $H^1 = J^1 + K^2, H^2 = J^2 - K^1$, the algebra becomes $[J^3, H^{1,2}] = \pm iH^{2,1}$ and $[H^1, H^2] = 0$, showing E_2 is a semidirect product of $\mathbf{SO}(2)$ and T_2 : $E_2 = \mathbf{SO}(2) \ltimes T_2$

To find the irreducible representations of E_2 , we use Wigner's classification again. For $\mathbf{H} = \begin{pmatrix} H^1 \\ H^2 \end{pmatrix}$ with $\mathbf{H}|\Pi, \alpha\rangle = \Pi|\Pi, \alpha\rangle$,

Orbit	$\hat{\Pi}$	$H\hat{\Pi}$
$\Pi^2 = c^2$	$(1, 0)$	e ; anything
$\Pi^2 = 0$	$(0, 0)$	$\mathbf{SO}(2)$

$\hat{\Pi} = (1, 0)$ corresponds to continuous spin states, which we will neglect here.

For $\hat{\Pi} = (0, 0)$, the little group is $\mathbf{SO}(2)$, which has a one-dimensional representation $D(R(\omega)) = e^{i\omega\lambda}$ with $\lambda = 0, \pm\frac{1}{2}, \pm 1, \pm\frac{3}{2}, \dots$.

Therefore, for massless particles, we write $|p, \alpha\rangle \rightarrow |p, \lambda\rangle$ with

$$U(\Lambda) |p, \lambda\rangle = e^{i\lambda\omega}(L^{-1}(\Lambda p)\Lambda L(p)) |\Lambda p, \lambda\rangle.$$

λ is called the helicity. Note that γ doesn't have spin.

Case 3 - $\hat{p} = (0, 0)$, $H\hat{p} = L_+^\uparrow$ This case corresponds to the vacuum states. For simplicity, we choose the trivial representation $|0\rangle$.

2.2.2 Weyl Spinor Representation of $\mathbf{SL}(n, \mathbb{C}) \sim L_+^\uparrow$

Consider the Pauli matrices,

$$\sigma^1 = \begin{pmatrix} & 1 \\ 1 & \end{pmatrix}, \quad \sigma^2 = \begin{pmatrix} & -i \\ i & \end{pmatrix}, \quad \sigma^3 = \begin{pmatrix} 1 & \\ & -1 \end{pmatrix}.$$

We define the 4-pauli vectors as

$$\sigma^\mu = (\mathbb{1}, \boldsymbol{\sigma}) \implies \sigma_\mu = (\mathbb{1}, -\boldsymbol{\sigma}), \quad \bar{\sigma}^\mu = (\mathbb{1}, -\boldsymbol{\sigma}).$$

If we consider the 2x2 matrices $[x] = x^\mu \sigma_\mu$, for $A \in \mathbf{SL}(2, \mathbb{C})$, we have that $[x]_A = A[x]A^\dagger$ is a Lorentz transformation;

$$\det[x] = x^2, \quad x_A^2 = \det[x]_A = \det(A[x]A^\dagger) = x^2.$$

From this, we can find four different representations for L_+^\uparrow :

- Trivial representation; $\psi_\alpha \rightarrow A_\alpha^\beta \psi_\beta \sim A\psi$
- Conjugate representation; $\psi_{\dot{\alpha}} \rightarrow (A^*)_{\dot{\alpha}}^{\dot{\beta}} \psi_{\dot{\beta}} \sim \psi A^\dagger$
- Transpose representation $\psi^\alpha \rightarrow (A^\top)^{-1}{}^\alpha_\beta \psi^\beta \sim \psi A^{-1}$
- Hermite representation $\psi^{\dot{\alpha}} \rightarrow \bar{A}^{\dot{\alpha}}_{\dot{\beta}} \psi^{\dot{\beta}} \sim \bar{A}\psi$. We define $\bar{A} = (A^\dagger)^{-1}$.

Note that, because L_+^\uparrow has $\det = 1$, $A^{-1} = A^\top$ and therefore we only have lower indices. If we had a unitary representation, $\bar{A} = A$, and would've only undotted indices.

Further, note that we use the levi-civita symbol to lower and raise indices:

$$\epsilon^{\alpha\beta} = \epsilon_{\alpha\beta} = \epsilon^{\dot{\alpha}\dot{\beta}} = \epsilon_{\dot{\alpha}\dot{\beta}} = \begin{pmatrix} & 1 \\ -1 & \end{pmatrix}.$$

From the condition that $\det A = 1$, the generators must be such that $\text{Tr } \omega = 0 \implies \omega = \frac{i}{2}(\boldsymbol{\alpha} + i\boldsymbol{\beta}) \cdot \boldsymbol{\sigma}$. Then,

$$A = \exp\left(\frac{i}{2}(\boldsymbol{\alpha} + i\boldsymbol{\beta}) \cdot \boldsymbol{\sigma}\right), \quad \bar{A} = \exp\left(\frac{i}{2}(\boldsymbol{\alpha} - i\boldsymbol{\beta}) \cdot \boldsymbol{\sigma}\right).$$

Therefore, the general representation of $\mathbf{SL}(2, \mathbb{C}) \sim L_+^\uparrow$ is

$$D^{m,n} = \varphi_{\alpha_1 \dots \alpha_m}^{\dot{\beta}_1 \dots \dot{\beta}_n} = \exp\left(\frac{i}{2}(\boldsymbol{\alpha} + i\boldsymbol{\beta}) \cdot \boldsymbol{\sigma}\right) \exp\left(\frac{i}{2}(\boldsymbol{\alpha} - i\boldsymbol{\beta}) \cdot \boldsymbol{\sigma}\right).$$

Another way to derive is to start by rewriting $\mathbf{M} = \frac{1}{2}(\mathbf{J} + i\mathbf{K})$, $\mathbf{N} = \frac{1}{2}(\mathbf{J} - i\mathbf{K})$. By writing this, \mathbf{M} and \mathbf{N} commute with each other and have their own $\mathfrak{su}(2)$ algebra. Therefore,

$$\Lambda = e^{i(\omega \cdot \mathbf{J} + \mathbf{v} \cdot \mathbf{K})} = e^{i\mathbf{M} \cdot (\mathbf{w} - i\mathbf{v})} e^{i\mathbf{N} \cdot (\mathbf{w} + i\mathbf{v})}.$$

We now consider the (1/2,0) representation. We have

$$\mathbf{M} = \frac{\sigma}{2}, \quad \mathbf{N} = 0 \implies \mathbf{J} = \frac{\sigma}{2}, \quad \mathbf{K} = -\frac{i\sigma}{2}.$$

The objects transform under this representation are called left-handed spinors ψ_L . These transform

$$(\psi_L)_\alpha \rightarrow A_\alpha^\beta \psi_\beta, \quad A_\alpha^\beta = \exp\left(i\frac{\mathbf{w} \cdot \boldsymbol{\sigma}}{2} + \frac{\mathbf{u} \cdot \boldsymbol{\sigma}}{2}\right).$$

Similarly, the (0,1/2) representation has

$$\mathbf{M} = 0, \quad \mathbf{N} = \frac{\sigma}{2} \implies \mathbf{J} = \frac{\sigma}{2}, \quad \mathbf{K} = \frac{i\sigma}{2}.$$

The objects that transform under this representation are called right-handed spinors ψ_R . These transform

$$(\psi_R)^{\dot{\beta}} \rightarrow \bar{A}^{\dot{\alpha}}_{\dot{\beta}} (\psi_R)^{\dot{\beta}}, \quad \bar{A}^{\dot{\alpha}}_{\dot{\beta}} = \exp\left(i\frac{\mathbf{w} \cdot \boldsymbol{\sigma}}{2} - \frac{\mathbf{u} \cdot \boldsymbol{\sigma}}{2}\right).$$

Lastly, the (1/2,1/2) representation can be written

$$(\psi_L)^\alpha (\sigma^\mu)_{\alpha\dot{\beta}} (\psi_R)^{\dot{\beta}}.$$

This is an ordinary 4-vector; recall that $x^\mu \sim [x] \rightarrow A[x]A^\dagger$.

2.2.3 Dirac Spinor Representation

For theories with parity symmetry, Dirac spinors are used to include both Left-handed spinors as well as Right-handed spinors. We let $\psi = \begin{pmatrix} \chi_\alpha \\ \bar{\psi}^{\dot{\alpha}} \end{pmatrix}$. The Lorentz transformation is

$$\begin{aligned} D(\Lambda) &= \begin{pmatrix} \exp\left(\frac{i}{2}\boldsymbol{\sigma}(\boldsymbol{\omega} - i\mathbf{u})\right) & 0 \\ 0 & \exp\left(\frac{i}{2}\boldsymbol{\sigma}(\boldsymbol{\omega} + i\mathbf{u})\right) \end{pmatrix} \\ &= \exp\left(i\boldsymbol{\omega} \cdot \boldsymbol{\Sigma} + \frac{1}{2}\mathbf{u} \cdot \boldsymbol{\alpha}\right), \quad \boldsymbol{\Sigma} = \frac{1}{2}\begin{pmatrix} \boldsymbol{\sigma} & 0 \\ 0 & \boldsymbol{\sigma} \end{pmatrix}, \quad \boldsymbol{\alpha} = \begin{pmatrix} -\boldsymbol{\sigma} & 0 \\ 0 & \boldsymbol{\sigma} \end{pmatrix}. \end{aligned}$$

$\boldsymbol{\Sigma}$ is a representation of \mathbf{J} , and $\boldsymbol{\alpha}$ is a representation of \mathbf{K} . The generator algebra is such that

$$\Sigma^i \Sigma^k = \alpha^i \alpha^k = \delta^{ik} + i\epsilon^{ikl} \Sigma^l, \quad [\Sigma^i, \gamma^0] = [\alpha^i, \gamma^0] = 0.$$

where

$$\gamma^0 = \begin{pmatrix} 0 & \mathbb{1} \\ \mathbb{1} & 0 \end{pmatrix}, \quad \gamma^i = \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix}.$$

These are known as the Dirac gamma matrices. These have an algebra,

$$\{\gamma^\mu, \gamma^\nu\} = 2g^{\mu\nu} \times \mathbb{1}.$$

2.3 Weyl Formalism

Lec 25-26

We want a Lagrangian that:

- Is Lorentz invariant,
- Has at most 2 derivatives and 2 fields,
- Has a real action,
- Has a U(1) symmetry ($\chi \rightarrow e^{i\alpha}\chi$). Experimentally, every 1/2 has a conserved charge, for example, lepton/baryon number, electric charge.

The kind of left-handed objects we can have are

$$\chi_\alpha, \quad \chi_\alpha^*, \quad \partial^\mu, \quad \sigma_{\alpha\dot{\alpha}}^\mu, \quad \bar{\sigma}^{\mu\dot{\alpha}\alpha}, \quad \epsilon_{\alpha\beta}.$$

For a bilinear \mathcal{L} , there are three possibilities:

1. $\mathcal{L} = c\chi_\alpha^* \bar{\sigma}^{\mu\dot{\alpha}\beta} (\partial_\mu \chi_\beta)$. Taking the complex conjugate then integrating by parts, realness requires that c^* is purely imaginary; from convention, we choose $c = i$.
2. $\mathcal{L} = \chi_\alpha \epsilon^{\alpha\beta} \chi_\beta$. This is not U(1) invariant. This corresponds to the Majorana mass, for neutrinos without charge.
3. $\mathcal{L} = (\partial_\mu \chi_\alpha) \epsilon^{\alpha\beta} (\partial^\mu \chi_\beta)$. This is not U(1) invariant either.

Therefore, we write the action

$$S = \int d^4x i\chi_\alpha^* \bar{\sigma}^{\mu\dot{\alpha}\alpha} (\partial_\mu \chi_\alpha) = \int d^4x i\bar{\chi} \not{\partial} \chi, \quad \not{\partial} \equiv \bar{\sigma}^\mu \partial_\mu. \quad (2.1)$$

From the Euler-Lagrange equation, we obtain

$$\bar{\sigma}^{\mu\dot{\alpha}\beta} \partial_\mu \chi_\beta = 0, \quad (2.2)$$

known as the (left-handed) Weyl equation.

This is consistent with the massless Klein-Gordon equation.

The plain wave solution is

$$\begin{aligned}\chi_L &= \int \frac{d^3p}{\sqrt{(2\pi)^3 2\omega_p}} \left[a_{p-} \begin{pmatrix} 0 \\ 1 \end{pmatrix} e^{-ipx} + b_{p+}^\dagger \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{ipx} \right] \\ \chi_L^\dagger &= \int \frac{d^3p}{\sqrt{(2\pi)^3 2\omega_p}} \left[a_{p-}^\dagger \begin{pmatrix} 0 \\ 1 \end{pmatrix} e^{ipx} + b_{p+} \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{-ipx} \right].\end{aligned}$$

Similarly, the right-handed Lagrangian and the corresponding equation are

$$\mathcal{L} = \pm i \psi^{*\alpha} \sigma_{\alpha\dot{\beta}}^\mu (\partial_\mu \psi^{\dot{\beta}}) \implies \sigma_{\alpha\dot{\beta}}^\mu \partial_\mu \psi^{\dot{\beta}} = 0.$$

The plain wave solution is

$$\psi_R = \int \frac{d^3p}{\sqrt{(2\pi)^3 2\omega_p}} \left[a_{p-} \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{-ipx} + b_{p+}^\dagger \begin{pmatrix} 0 \\ 1 \end{pmatrix} e^{ipx} \right].$$

2.3.1 Majorana Theory

To add mass to our theory, we consider the Majorana mass term. The corresponding action is

$$S = \int d^4x \left[i \psi_\alpha^* \bar{\sigma}^{\mu\dot{\alpha}\alpha} \partial_\mu \psi_\alpha - \frac{m}{2} \psi_\alpha \epsilon^{\alpha\beta} \psi_\beta + \text{h.c.} \right].$$

The equations of motion are

$$i \bar{\sigma}^{\mu\dot{\alpha}\beta} \partial_\mu \psi_\beta = m (\psi^*)^{\dot{\alpha}}, \quad -i \partial_\mu \psi_\alpha^* \bar{\sigma}^{\mu\alpha\beta} = m \psi^\beta.$$

With the ansatz $\psi_\beta = x_\beta e^{-ipx} + y_\beta e^{ipx}$, we can reduce the equations to

$$(p \cdot \bar{\sigma})x = my^\dagger, \quad (p \cdot \bar{\sigma})y = -mx^\dagger, \iff (p \cdot \sigma)y^\dagger = mx, \quad (p \cdot \sigma)x^\dagger = -my.$$

The solutions are such that

$$x_\alpha(p, s) = \sqrt{p \cdot \sigma} \chi_s, \quad y_\alpha(p, s) = (2s) \sqrt{p \cdot \sigma} \chi_s,$$

giving us

$$\psi_\alpha(x) = \int \frac{d^3p}{\sqrt{(2\pi)^3 2\omega_p}} \sum_s (x_\alpha(p, s) a_{p,s} e^{-ipx} + y_\alpha(p, s) a_{p,s}^\dagger e^{ipx}).$$

Enforcing the commutator relations $\{a_{\mathbf{p},s}, a_{\mathbf{p}',s'}^\dagger\} = \delta(\mathbf{p} - \mathbf{p}') \delta_{ss'}$, we obtain $\{\chi_\alpha(\mathbf{x}, t), \chi_\beta^\dagger(\mathbf{y}, t)\} = \sigma^0 \delta(\mathbf{x} - \mathbf{y})$.

Note that the Majorana theory is not invariant under $U(1)$ transformations, suitable for neutrinos.

2.4 Dirac Theory

2.4.1 Gamma Matrices

We define the Dirac gamma matrices (in **Weyl/Chiral basis**):

$$\gamma^0 = \begin{pmatrix} 0 & \mathbb{1} \\ \mathbb{1} & 0 \end{pmatrix}, \quad \gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \bar{\sigma}^\mu & 0 \end{pmatrix}$$

The gamma matrices have respect the Clifford algebra and are Lorentz generators:

$$\{\gamma^\mu, \gamma^\nu\} = 2g^{\mu\nu} \mathbb{1}, \quad [\gamma^\mu, \gamma^\nu] \frac{i}{2} = S^{\mu\nu}.$$

The γ^5 matrix is defined $\gamma^5 = \gamma_5 = i\gamma^0\gamma^1\gamma^2\gamma^3$. It holds that

$$\gamma_5^2 = 1, \quad \gamma_5 = \begin{pmatrix} -\mathbb{1} & 0 \\ 0 & \mathbb{1} \end{pmatrix}. \tag{2.3}$$

It is known as the Chirality operators, because one can project the Dirac spinors onto left/right handed Weyl spinors:

$$P_L = \frac{1 - \gamma_5}{2} = \begin{pmatrix} \mathbb{1} & 0 \\ 0 & 0 \end{pmatrix}, \quad P_R = \frac{1 + \gamma_5}{2} = \begin{pmatrix} 0 & 0 \\ 0 & \mathbb{1} \end{pmatrix}. \tag{2.4}$$

Contraction identities include

$$\begin{aligned}\gamma^\mu \gamma_\mu &= 4I_4 \\ \gamma^\mu \gamma^\nu \gamma_\mu &= -2\gamma^\nu \\ \gamma^\mu \gamma^\nu \gamma^\rho \gamma_\mu &= 4\eta^{\nu\rho} I_4 \\ \gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma \gamma_\mu &= -2\gamma^\sigma \gamma^\rho \gamma^\nu.\end{aligned}$$

Trace identities include

$$\begin{aligned}\text{tr} \gamma^\mu &= 0 \\ \text{tr} \gamma^5 &= 0 \\ \text{tr}(\text{odd \# of } \gamma^\mu) &= 0 \\ \text{tr}(\gamma^5 \text{ odd \# of } \gamma^\mu) &= 0 \\ \text{tr}(\gamma^\mu \gamma^\nu) &= 4\eta^{\mu\nu} \\ \text{tr}(\gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma) &= 4(\eta^{\mu\nu} \eta^{\rho\sigma} - \eta^{\mu\rho} \eta^{\nu\sigma} + \eta^{\mu\sigma} \eta^{\nu\rho}) \\ \text{tr}(\gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma \gamma^5) &= -4i\epsilon^{\mu\nu\rho\sigma}.\end{aligned}$$

2.4.2 Dirac Formalism

To add mass to the theory while keeping $U(1)$ symmetry, we consider a Lagrangian of the form

$$\mathcal{L} = i(\psi_L^\dagger)_\alpha \bar{\sigma}^{\mu\alpha\dot{\beta}} \partial_\mu \psi_{L\dot{\beta}} + (\psi_R^\dagger)^\alpha \sigma_{\alpha\dot{\beta}}^\mu \partial_\mu \psi_R^{\dot{\beta}} - m(\psi_R^\dagger)^\alpha (\psi_{L\dot{\beta}})_\alpha - m(\psi_R)^\alpha (\psi_{L\dot{\beta}})_\alpha = \bar{\psi}(i\cancel{\partial} - m)\psi. \quad (2.5)$$

The equation of motion is

$$(i\cancel{\partial} - m)\psi = 0. \quad (2.6)$$

Letting $\psi = \begin{pmatrix} x_\alpha \\ y^{\dagger\dot{\beta}} \end{pmatrix} e^{-ipx}$, we obtain, from the two-component spinor results,

$$\psi = u_{\mathbf{p},s} e^{-ipx} + v_{\mathbf{p},x} e^{ipx}, \quad u_{\mathbf{p},s} = \begin{pmatrix} \sqrt{p \cdot \sigma} \chi_s \\ \sqrt{p \cdot \bar{\sigma}} \chi_s \end{pmatrix}, \quad v_{\mathbf{p},s} = \begin{pmatrix} \sqrt{p \cdot \sigma} \chi_{-s} \\ -\sqrt{p \cdot \bar{\sigma}} \chi_{-s} \end{pmatrix}. \quad (2.7)$$

By definition, $(\cancel{p} - m)u = (\cancel{p} + m)v = 0$. The normalization is such that $u^\dagger u = v^\dagger v = 2E_p$ and $\bar{u}u = -\bar{v}v = 2m$.

The u and v are orthogonal to each other ($\bar{u}v = \bar{v}u = 0$). While $u^\dagger v, v^\dagger u \neq 0$, it holds $u^\dagger(\mathbf{p})v^\dagger(-\mathbf{p}) = v^\dagger(-\mathbf{p})u(\mathbf{p}) = 0$.

Furthermore,

$$\sum_s u_s \bar{u}_s = (\cancel{p} + m), \quad \sum_s v_s \bar{v}_s = (\cancel{p} - m). \quad (2.8)$$

This result is known as the spin sum statistics.

The Dirac field is quantized as

$$\psi(x) = \int \frac{d^3}{\sqrt{(2\pi)^3 2\omega_p}} \sum_s \left(u_{\mathbf{p}}^{(s)} b_{\mathbf{p}}^{(s)} e^{-ipx} + v_{\mathbf{p}}^{(s)} c_{\mathbf{p}}^{\dagger(s)} e^{ipx} \right). \quad (2.9)$$

Imposing $\{b_{\mathbf{p},r}, b_{\mathbf{p}',r}^\dagger\} = \{c_{\mathbf{p},r}, c_{\mathbf{p}',r}^\dagger\} = \delta(\mathbf{p} - \mathbf{p}')\delta_{rr'}$, we obtain

$$\{\psi_\alpha(\mathbf{x}, t), \psi_\beta^\dagger(\mathbf{y}, t)\} = \delta(\mathbf{x} - \mathbf{y}). \quad (2.10)$$

2.4.3 Free Dirac Theory

The canonical momentum is

$$\Pi_\alpha = \frac{\partial \mathcal{L}}{\partial(\partial_0 \psi_\alpha)} = i\bar{\psi}\gamma^0 = i\psi^\dagger \implies \{\psi_\alpha(\mathbf{x}, t), i\psi_\beta^\dagger(\mathbf{y}, t)\} = i\delta(\mathbf{x} - \mathbf{y}). \quad (2.11)$$

The Hamiltonian is

$$H = \int d^3p \omega_p \sum_r (b_{\mathbf{p},r}^\dagger b_{\mathbf{p},r} + c_{\mathbf{p},r}^\dagger c_{\mathbf{p},r}) \quad (2.12)$$

The conserved current and charge are

$$J^\mu = \bar{\psi}\gamma^\mu\psi \implies Q = \int d^3p \sum_r (b_{\mathbf{p},r}^\dagger b_{\mathbf{p},r} - c_{\mathbf{p},r}^\dagger c_{\mathbf{p},r}). \quad (2.13)$$

We interpret b^\dagger as a particle of charge 1, c^\dagger as a particle of charge -1 , and $\delta(0)$ the charge of vacuum.

2.5 Discrete Symmetries

- (a) The parity operator γ^0 , when acted on ψ , switches ψ_L with ψ_R . Fields and states have internal parity, ± 1 or $\pm i$.
- (b) The charge conjugation operator switches $b_{\mathbf{p},r}$ with $c_{\mathbf{p},r}$ and vice versa. Since we defined C to conjugate as well, we need $C\psi \rightarrow A\psi^*$, meaning we need the v spinor out of u^* , giving us

$$Au^* = v \implies A = \begin{pmatrix} & \epsilon \\ -\epsilon & \end{pmatrix} = i\gamma^2 \implies C : \psi \rightarrow -i\gamma^2\psi^*. \quad (2.14)$$

We have that the Dirac theory has CP symmetry; this is generalized to all Gauge interactions, only broken by the Higgs interaction.

3 Interacting Fields

3.1 Formulation

3.1.1 Dyson's Formula

Lec 8,9

For a system with an interaction, term, the Hamiltonian can be written $H = H_0 + H_{\text{int}}$. We define the interaction action field to be

$$\phi_I(t, \mathbf{x}) = e^{iH_0(t-t_0)} \phi(t_0, \mathbf{x}) e^{-iH_0(t-t_0)} = e^{iH_0(t-t_0)} \left(e^{-iH(t-t_0)} \phi(t, \mathbf{x}) e^{iH(t-t_0)} \right) e^{-iH_0(t-t_0)}.$$

In other words, the interaction field is what the field would evolve (from t_0 to t) if it weren't for the interacting terms. Now, we define the time evolution operator, which gives a concise expression of the full field:

$$U(t, t_0) = e^{iH_0(t-t_0)} e^{-iH(t-t_0)} \implies \phi(t, \mathbf{x}) = U^\dagger(t, t_0) \phi_I(t, \mathbf{x}) U(t, t_0).$$

Taking the derivative of the time evolution operator,

$$i \frac{\partial}{\partial t} U(t, t_0) = \left(e^{iH_0(t-t_0)} H_{\text{int}} e^{-iH_0(t-t_0)} \right) U(t, t_0) = H_I(t) U(t, t_0),$$

we can see that $H_I(t)$ is the interaction Hamiltonian written in the interaction picture - evolving with the free Hamiltonian. The solution for this differential equation - with $U(t_0, t_0) = 1$ - is a power series:

$$\begin{aligned} U(t, t_0) = & 1 + (-i) \int_{t_0}^t dt_1 H_I(t_1) + (-i)^2 \int_{t_0}^t dt_1 \int_{t_0}^{t_1} dt_2 H_I(t_1) H_I(t_2) \\ & + (-i)^3 \int_{t_0}^t dt_1 \int_{t_0}^{t_1} dt_2 \int_{t_0}^{t_2} dt_3 H_I(t_1) H_I(t_2) H_I(t_3) + \dots \end{aligned}$$

Note that the successive integration limits get smaller and the interaction Hamiltonians are time-ordered. To get rid of the time-ordering operators, we note that

$$\int_{t_0}^t dt_1 \int_{t_0}^{t_1} dt_2 \dots \int_{t_0}^{t_{n-1}} dt_n H_I(t_1) \dots H_I(t_n) = \frac{1}{n!} \int_{t_0}^t dt_1 \dots dt_n T[H_I(t_1) \dots H_I(t_n)].$$

Refer to Peskin 4.21 for a “proof”⁶ - it is analogous to finding the volume of an n -simplex. With this, we can write $U(t, t_0)$ in a compact form:

$$\begin{aligned} U(t, t_0) &= 1 + (-i) \int_{t_0}^t dt_1 H_I(t_1) + \frac{(-i)^2}{2!} \int_{t_0}^t dt_1 dt_2 T[H_I(t_1) H_I(t_2)] + \dots \\ &= T \exp \left(-i \int_{t_0}^t dt' H_I(t') \right) = T \exp \left[i \int_{t_0}^t \int d^3x' \mathcal{L}'(\phi_I(\lambda')) \right] \end{aligned} \quad (3.1)$$

Note that

- In this form, it is evident (from the limits of integrals) that $U(t_1, t_2) U(t_2, t_3) = U(t_1, t_3)$, and $U(t_1, t_3) U^\dagger(t_2, t_3) = U(t_1, t_2)$;
- The time ordering operator is invariant - order of events doesn't change for timelike events and all ϕ commute for spacelike events - the Lagrangian is invariant, and the integral $\int dt \int d^3x'$ is invariant if we let t, t_0 to $\pm\infty$.

We first claim that as $t \rightarrow \pm\infty$, interactions effectively turn off; asymptotically, we will have free field/particles, each state approaching the asymptotic state⁷. If we let $|\psi\rangle$ as the free states and $|\psi\rangle_{\text{in}}$ and $|\psi\rangle_{\text{out}}$ as the interacting states, we have

$$\lim_{t \rightarrow -\infty} e^{-iHt} |\psi(t=0)\rangle_{\text{in}} = e^{-iH_0t} |\psi(t=0)\rangle, \quad \lim_{t \rightarrow \infty} e^{-iHt} |\psi(t=0)\rangle_{\text{out}} = e^{-iH_0t} |\psi(t=0)\rangle.$$

In other words,

$$|\psi\rangle_{\text{in}} = \lim_{t \rightarrow -\infty} e^{iHt} e^{-iH_0t} |\psi\rangle, \quad |\psi\rangle_{\text{out}} = \lim_{t \rightarrow \infty} e^{iHt} e^{-iH_0t} |\psi\rangle.$$

We're interested in scattering amplitudes, defined as the probability of measuring $|\chi\rangle_{\text{out}}$ given an in state $|\psi\rangle_{\text{in}}$. We have

$$\langle \chi_{\text{out}} | \psi_{\text{in}} \rangle = \lim_{t' \rightarrow -\infty} \lim_{t \rightarrow \infty} \langle \chi | U(t, t') | \psi \rangle = S_{\chi\psi},$$

where we define $S = \lim_{t, t' \rightarrow \pm\infty} U(t, t')$, which is also called the scattering matrix. The S -matrix is unitary; $S^\dagger S = \mathbb{1}$, and commutes with/preserves free energy; $[S, H_0] = 0$. Therefore,

$$S = T \exp \left[-i \int_{-\infty}^{\infty} d^4x H \right]. \quad (3.2)$$

This is known as Dyson's equation.

3.1.2 Correlation Function

The evolution of $|0\rangle$ with H , in terms of the eigenvalues of H is

$$e^{-iHT} |0\rangle = e^{-iE_0T} |\Omega\rangle \langle \Omega|0\rangle + \sum_{n \neq 0} e^{-iE_nT} |n\rangle \langle n|0\rangle \implies |\Omega\rangle = \lim_{T \rightarrow \infty (1-i\epsilon)} \left(e^{-iE_0T} \langle \Omega|0\rangle \right)^{-1} e^{-iHT} |0\rangle,$$

where we have used the fact that E_0 is dies slowest for a slightly imaginary time which turns into real exponential factor.

⁶<http://scipp.ucsc.edu/~haber/ph215/TimeOrderedExp.pdf>

⁷This really isn't true because of self and vacuum interactions, but we will come back here for renormalization.

Shifting T by t_0 and inserting an exponential factor of H_0 (since $H_0 |0\rangle = |0\rangle$),

$$|0\rangle = \lim_{T \rightarrow \infty(1-i\epsilon)} \left(e^{-iE_0(t_0 - (-T))} \langle \Omega | 0 \rangle \right)^{-1} U(t_0, -T) |0\rangle.$$

Assuming $x^0 > y^0$,

$$\frac{\langle \Omega | \phi(x) \phi(y) | \Omega \rangle}{\langle \Omega | \Omega \rangle} = \lim_{T \rightarrow \infty(1-i\epsilon)} \frac{\langle 0 | U(T, x^0) \phi_I(x) U(x^0, y^0) \phi_I(y) U(y^0, -T) | 0 \rangle}{\langle 0 | U(T, -T) | 0 \rangle},$$

where we have canceled out a factor of $\left(\langle 0 | \Omega \rangle^2 e^{-iE_0(2T)} \right)^{-1}$ from both sides.

Hence, the correlation function is written

$$\langle \Omega | T \{ \phi(x) \phi(y) \} | \Omega \rangle = \lim_{T \rightarrow \infty(1-i\epsilon)} \frac{\langle 0 | T \left\{ \phi_I(x) \phi_I(y) \exp \left[-i \int_{-T}^T dt H_I(t) \right] \right\} | 0 \rangle}{\langle 0 | T \left\{ \exp \left[-i \int_{-T}^T dt H_I(t) \right] \right\} | 0 \rangle} \quad (3.3)$$

3.1.3 Wick's Theorem

Recall that Φ_I are fields that can be expressed in ladder operators, which are easier to work with in normal ordering. For this, we introduce **Wick's theorem**, a theorem that relates time ordering T to normal ordering $::$. First, we define the **contraction**, defined

$$T(\phi^a(x) \phi^b(y)) =: \phi^a(x) \phi^b(y) : + \overline{\phi^a(x) \phi^b(y)}.$$

We can find an explicit form for the contraction:

- For the $x^0 > y^0$ case, we have

$$T[\phi^a(x) \phi^b(y)] = \phi^a(x) \phi^b(y) = (\phi^{a+}(x) + \phi^{a-}(x)) (\phi^{b+}(y) + \phi^{b-}(y)) =: \phi^a \phi^b : + \delta_{ab} \Delta_+(x - y),$$

- For $x^0 < y^0$, we have

$$T[\phi^a(x) \phi^b(y)] =: \phi^a \phi^b : + \delta_{ab} \Delta_+(y - x).$$

Hence, we obtain

$$\overline{\phi^a(x) \phi^b(y)} = \delta_{ab} \int \frac{d^4 k}{(2\pi)^4} e^{-ik(x-y)} \frac{i}{k^2 - m^2 + i\epsilon}.$$

Now, we can state Wick's theorem:

$$\begin{aligned} T(\phi_1 \cdots \phi_n) &= : \phi_1 \cdots \phi_n : \\ &\quad + \overline{\phi_1 \phi_2} : \phi_3 \cdots \phi_n : + \overline{\phi_1 \phi_3} : \phi_2 \phi_4 \cdots \phi_n : + \cdots \\ &\quad + \overline{\phi_1 \phi_2} \overline{\phi_3 \phi_4} : \phi_5 \cdots \phi_n : \\ &\quad \vdots \end{aligned} \quad (3.4)$$

We prove this by induction. Consider n fields ϕ_1, \dots, ϕ_n with times $\phi_1^0 \geq \phi_2^0 \geq \dots \phi_n^0$. If $\phi_2 \cdots \phi_n$ were in Wick-expression - $T\phi_1\phi_2 =: \phi_1\phi_2 : + \overline{\phi_1\phi_2}$, which is the zeroth term, is in Wick ordering by definition - we can multiply by ϕ_1 on the left. Since all fields are time-ordered already,

$$T(\phi_1 \cdots \phi_n) = \phi_1 (: \phi_2 \cdots \phi_n : + \overline{\phi_2 \phi_3} : \phi_4 \cdots \phi_n : + \cdots).$$

Now, let ϕ_1^+ and ϕ_1^- be the creation/annihilation parts of ϕ_1 . Then, we have

$$T(\phi_1 \cdots \phi_n) = \phi_1^+ : \phi_2 \cdots \phi_n : + \phi_1^- : \phi_2 \cdots \phi_n : + \phi_1 + (\phi_1^+ + \phi_1^-) \overline{\phi_2 \phi_3} : \phi_4 \cdots \phi_n : + \cdots.$$

Let's focus on the non-contraction terms for a minute. They can be written

$$\phi_1^+ : \phi_2 \cdots \phi_n : + \phi_1^- : \phi_2 \cdots \phi_n : = : \phi_1^+ \phi_2 \cdots \phi_n : + : \phi_2 \cdots \phi_n \phi_1^- : + [\phi_1^-, : \phi_2 \cdots \phi_n :].$$

From definition, the first two terms are $: \phi_1 \phi_2 \cdots \phi_n :$. The commutator can be explicitly evaluated:

$$\begin{aligned} [\phi_1^-, : \phi_2 \cdots \phi_n :] &= [\phi_1^-, \phi_2^+ : \phi_3 \cdots \phi_n :] + [\phi_1^-, \phi_2^- : \phi_3 \cdots \phi_n :] \\ &= [\phi_1^-, \phi_2^+] : \phi_3 \cdots \phi_n : + (\phi_2^+ + \phi_2^-) [\phi_1^-, : \phi_3 \cdots \phi_n :] + \cancel{[\phi_1^-, \phi_2^-] : \phi_3 \cdots \phi_n :}. \end{aligned}$$

Using the fact that $[\phi_1^-, \phi_2^+] = \overline{\phi_1 \phi_2}$ for $x_1^0 > x_2^0$, we get

$$[\phi_1^-, : \phi_2 \cdots \phi_n :] = \sum_{i=2}^n \phi_2 \cdots \phi_{i-1} \overline{\phi_1 \phi_i} \phi_{i+1} \cdots \phi_n.$$

Keeping in mind that all contractions are complex numbers, we can deduce that the contraction terms are

$$(\phi_1^+ + \phi_1^-) \overline{\phi_2 \phi_3} : \phi_4 \cdots \phi_n : + \cdots = \overline{\phi_2 \phi_3} : \phi_1 \phi_4 \cdots \phi_n : + \overline{\phi_2 \phi_3} \sum_{i=4}^n \phi_4 \cdots \phi_{i-1} \overline{\phi_1 \phi_i} \phi_{i+1} \cdots \phi_n + \cdots.$$

In other words, multiplying a normal ordered sequence by ϕ_1 is the normal ordering sequence with ϕ_1 and all single contractions with ϕ_1 . Hence Wick's theorem is proved.

Example. Interaction with External Field [Lec 9, 10](#)

Let the interacting Hamiltonian of the external field be $H' = \lambda\phi(x)\rho(x)$. For boundary conditions, we let $\rho(x) \rightarrow 0$ for $t \pm \infty$. From Dyson's formula, we have

$$S = T \sum_{n=0}^{\infty} \frac{(-i\lambda)^n}{n!} \left(\int \rho(x)\phi(x) \cdot d^3x \right)^n.$$

From Wick's formula, we have to sum over every possible number of contractions:

$$\sum_{n,p} \frac{(-i\lambda)^n}{n!} \left(\int d^4x_1 d^4x_2 \rho(x_1)\rho(x_2) \overline{\phi(x_1)\phi(x_2)} \right)^p : \left(\int d^4x_3 \rho(x_3)\phi(x_3) \right)^{n-2p} : \frac{n!}{2^p(n-2p)!p!}.$$

Note that the combinatoric factor can be considered by choosing p pairs from n objects:

$$\binom{n}{2} \binom{n-2}{2} \dots \binom{n-(2p-2)}{2} \cdot \frac{1}{p!} = \frac{n!}{2^p(n-2p)!p!}.$$

If we redefine $k = n - 2p$, we get

$$S = A : \exp \left(-i\lambda \int d^4x \rho(x)\phi(x) \right) :, \quad A = \exp \left(\frac{1}{2} (-i\lambda)^2 \int d^4x_1 d^4x_2 \rho(x_1)\rho(x_2) \overline{\phi(x_1)\phi(x_2)} \right).$$

The Fourier transformation of the $\rho(x)$ is $\rho(x) = \int \frac{d^4k}{(2\pi)^4} \tilde{\rho}(k) e^{-ikx}$, we have

$$\int d^4x \rho(x)\phi(x) = \int \frac{d^3k}{(2\pi)^3 2\omega_k} (\tilde{\rho}(-k)a_k + \tilde{\rho}(k)a_k^\dagger)$$

From this, we can calculate the probability of creating n particles: $\langle k_1 \dots k_n | S | 0 \rangle$; since the S matrix is acting on the vacuum state, we want to have n creation operators that exactly match the momenta $k_1 \dots k_n$;

$$\langle k_1 \dots k_n | S | 0 \rangle = A \tilde{\rho}(k_1) \dots \rho(k_n) (-i\lambda)^n \implies \langle k_1 | S | 0 \rangle = -i\lambda A \tilde{\rho}(k_1).$$

Recall that $\langle k_1 k_2 | S | 0 \rangle \sim \tilde{\rho}(k_1)$, which is the Fourier transform of the source. For a static source, no particles are created, but the ground/vacuum energy changes:

$$\langle 0 | S | 0 \rangle = A = \exp \left(\frac{(-i\lambda)^2}{2} \int \frac{d^4k}{(2\pi)^4} |\tilde{f}(k^0)|^2 |\tilde{\rho}(k)|^2 \frac{i}{k^2 - m^2 + i\epsilon} \right) = \exp(-i(\gamma_{\text{on}} + \gamma_{\text{off}} + E_0 T)).$$

This can be interpreted as the phase from turning the source on/off plus the phase from $E_0 T$, where T is the duration of the source. We have

$$E_0 = \frac{(-i\lambda)^2}{2T} \int \frac{d^4k}{(2\pi)^4} |f(k^0)|^2 |\tilde{\rho}(\mathbf{k})|^2 \frac{i}{k^2 - m^2 + i\epsilon} + \frac{-\gamma_{\text{on}} - \cancel{\gamma_{\text{off}}}}{T}.$$

From Parseval's theorem⁸, we have

$$E_0 = -\frac{\lambda^2}{2} \int \frac{d^3k}{(2\pi)^0} |\rho(\mathbf{k})|^2 \frac{1}{k^2 + m^2 - i\epsilon} = \frac{\lambda^2}{2} \int \rho(x_1)\rho(x_2) V(\mathbf{x}_1 - \mathbf{x}_2) d^3x_1 d^3x_2.$$

From the Fourier transform, we have

$$V(\mathbf{x}) = - \int \frac{d^3k}{(2\pi)^3} e^{i\mathbf{k} \cdot \mathbf{x}} \frac{1}{\mathbf{k}^2 + m^2 - i\epsilon} = - \int_{-\infty}^{\infty} \frac{1}{(2\pi)^2} \frac{1}{ir} \frac{k dk}{k^2 + m^2} e^{ikr} = -\frac{1}{4\pi r} e^{-mr}.$$

3.2 Feynman Diagrams

[Lec. 11-12](#)

The Feynman diagrams are a convenient way to express correlation functions. The rules in the position space to find the correlation function $\langle f | S | i \rangle$ are, with all connected, amputated diagrams,

1. For each propagator, add $D_F(x - y)$
2. For each vertex, add $(-i\lambda) \int d^4z$
3. For each incoming external line, add e^{-ipx} , for each outgoing external line, add e^{ipx}
4. Divide by the symmetry factor.

In the momentum space,

1. For each propagator, add $\tilde{D}_F = \frac{i}{k^2 - m^2 + i\epsilon}$
2. For each vertex, add $(-i\lambda)$, and conserve momentum
3. For each loop, add $\int \frac{d^4k}{(2\pi)^4}$;
4. Divide by the symmetry factor.

⁸<https://mathworld.wolfram.com/ParsevalsTheorem.html>

3.3 Scattering

Lec. 13-14

Because the transition amplitude is not L^2 , it is necessary to work in box normalization, characterized by

- Periodic boundary conditions: $\mathbf{k} = \frac{2\pi}{L}\mathbf{n}$;
- Box commutation relations: $[a_k^{\text{box}}, a_{k'}^{\dagger\text{box}}] = \delta_{kk'}$;
- State density $dn = \frac{V}{(2\pi)^3}d^3k$.

Furthermore, the Feynman rules don't change in box normalization; only the external states are changed:

$$\langle 0 | \phi(x) | k \rangle = e^{-ik \cdot x} \rightarrow \frac{1}{\sqrt{2\omega_k V}} e^{-ik \cdot x}.$$

Therefore,

$$\begin{aligned} \langle f | S - \mathbb{1} | i \rangle &= i(2\pi)^4 A_{fi} \delta^{(4)}(k_{\text{in}} - k_{\text{out}}) \prod_i \frac{1}{\sqrt{2E_i V}} \\ \implies |\langle f | S - \mathbb{1} | i \rangle|^2 &= |A_{fi}|^2 (2\pi)^4 \delta(k_{\text{in}} - k_{\text{out}}) \cdot VT \cdot \prod_i \frac{1}{(2E_i V)} \end{aligned}$$

where the index i is over all external states and we have used $\delta^2 k = \delta(k)\delta(0) = \frac{1}{(2\pi)^4} \int d^4x = \frac{VT}{(2\pi)^4}$. Furthermore, for a measurable quantity, we should cancel out V and T ; the quantity we are interested in, the **differential transitional probability**, is obtained from the transitional probability by

- Dividing by T ;
- Dividing by the flux of the initial particles;
- Multiplying by the density of the state factor for final states, $dN = \frac{V}{(2\pi)^3}d^3k$,

which ensures that the quantities are intrinsic to the process.

$$V \prod_{\text{init.}} \frac{1}{(2E_i V)} |A_{fi}|^2 \cdot D^{(n)}, \quad D^{(n)} = \prod_i \left(\frac{d^3 k_i}{(2\pi)^3 2E_i} \right) \cdot (2\pi)^4 \delta^{(4)}(k_{\text{in}} - k_{\text{out}}), \quad (3.5)$$

where $D^{(n)}$ is the **n-body phase space**, which is equal to the probability of scattering into a phase volume. We have that

1. The rate of a particle decaying into n is

$$d\Gamma = \frac{1}{2E_i} |A_{fi}|^2 D^{(n)};$$

from $d\Gamma$, we obtain Γ , the decay width, from which we get $\tau = \frac{1}{\Gamma}$, the characteristic lifetime of a particle.

2. The scattering cross section of a two-particle initial state is

$$d\sigma = \frac{1}{4E_T k_i} |A_{fi}|^2 D^{(n)},$$

in the center of mass frame.

Example. Two-body phase space can be calculated (in the center of momentum frame),

$$D^{(2)} = \frac{d^3 k_1}{(2\pi)^3 2E_1} \frac{d^3 k_2}{(2\pi)^3 2E_2} (2\pi)^4 \delta^{(3)}(k_1 + k_2) \delta(E_1 + E_2 - E_T) = \frac{k^2 dk d\Omega}{(2\pi)^2 \cdot 2E_1 \cdot 2E_2} \delta(E_1 + E_2 - E_T).$$

Further writing $\delta(E)$, we have $\delta(E_1 + E_2 - E_T) = \frac{\delta(k - k_0)}{|\partial_k E_1 + \partial_k E_2|_{k=k_0}}$. With $\frac{dE}{dk} = \frac{k}{E}$, we have

$$D^{(2)} = \frac{k^2 d\Omega}{k(E_1^{-1} + E_2^{-1}) \cdot 4\pi^2 \cdot 4E_1 E_2} = \frac{k d\Omega}{16\pi^2 E_T}. \quad (3.6)$$

For a 1-2 decay and 2-2 scattering, we obtain

$$\frac{d\Gamma}{d\Omega} = \frac{1}{32\pi^2 m_A^2} k_B |A_{fi}|^2, \quad \frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 E_T^2} \frac{k_f}{k_i} |A_{fi}|^2.$$

Example. Three-body phase space can be calculated (in the CoM frame),

$$D^{(3)} = \frac{1}{(2\pi)^3} \frac{1}{8E_1 E_2 E_3} k_1^2 dk_1 d\Omega_1 k_2^2 dk_2 d\Omega_{12} \delta(E_1 + E_2 + E_3 - E_T).$$

With $d\Omega_{12} = d(\cos \theta_{12}) d\phi_{12}$ and $dd(\cos \theta_{12} \delta(E_1 + E_2 + E_3 - E_T)) = \frac{E_3}{k_1 k_2}$, we obtain

$$D^{(3)} = \frac{1}{256\pi^5} dE_1 dE_2 d\Omega_1 d\phi_{12}.$$

3.3.1 Mandelstam Variables

The scattering amplitudes for an elastic 2-2 interaction are often written in terms of Mandelstam variables. The momenta in the center of mass frame can be written

$$k_1 = (E, 0, 0, p), \quad k'_1 = (E, p \sin \theta, 0, p \cos \theta), \quad k_2 = (E, 0, 0, -p), \quad k'_2 = (E, -p \sin \theta, 0, -p \cos \theta),$$

where θ is the scattering angle. We now write the definition of the Mandelstam variables and write them in terms of E , p , and θ :

$$\begin{aligned} s &= (k_1 + k_2)^2 = 4E^2 = E_T^2; \\ t &= (k_1 - k'_1)^2 = -4p^2 \sin^2 \left(\frac{\theta}{2} \right) = -\mathbf{q}^2 \\ u &= (k_1 - k'_2)^2 = -4p^2 \cos^2 \left(\frac{\theta}{2} \right) = -\mathbf{q}_c^2, \end{aligned}$$

where E_T is the total energy, \mathbf{q} is the momentum transfer from p_1 to p'_1 and \mathbf{q}_c is the momentum transfer in the cross channel. Note that s, t, u are not independent; $s + t + u = 4m^2$.

3.4 ϕ^3 Theory

3.4.1 $\phi\phi \rightarrow \phi\phi$

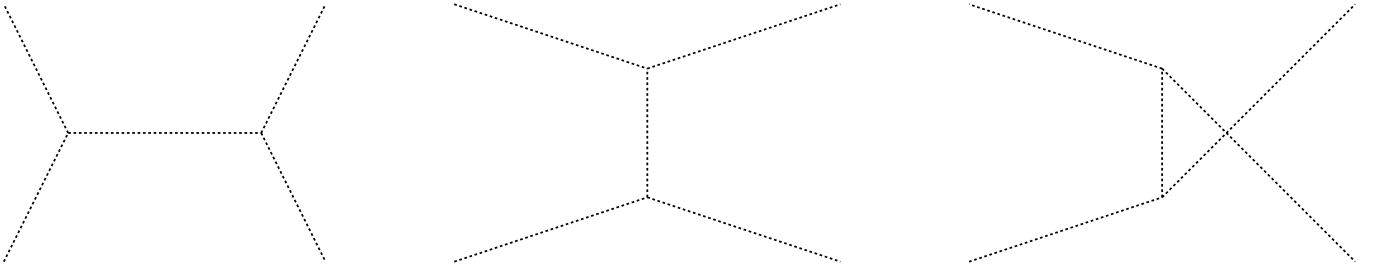


Figure 1: The tree-level diagrams for the $\phi\phi \rightarrow \phi\phi$ interaction in ϕ^3 theory.

The total scattering amplitude for the $\phi\phi \rightarrow \phi\phi$ interaction is

$$\begin{aligned} i\mathcal{M}_{\phi\phi \rightarrow \phi\phi} &= (-i\lambda)^2 \cdot i \left(\frac{1}{(k_1 + k_2)^2 - m^2 + i\epsilon} + \frac{1}{(k_1 - k'_1)^2 - m^2 + i\epsilon} + \frac{1}{(k_1 - k'_2)^2 - m^2 + i\epsilon} \right) \\ &= -i\lambda^2 \left(\frac{1}{s - m^2} + \frac{1}{t - m^2} + \frac{1}{u - m^2} \right). \end{aligned}$$

It is made explicit in this form that this interaction has a crossing symmetry.

3.5 ϕ^4 Theory

3.6 Yukawa Theory

3.7 Quantum Electrodynamics

3.7.1 $e^+e^- \rightarrow e^+e^-$, Bhabha Scattering

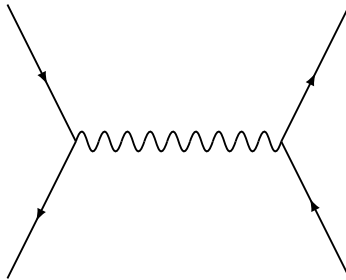


Figure 2: The tree-level diagram for the $e^+e^- \rightarrow \mu^+\mu^-$ interaction in QED

3.7.2 $e^-e^- \rightarrow e^-e^-$, Moller Scattering

3.7.3 $e^-\gamma \rightarrow e^-\gamma$, Compton Scattering

3.7.4 $e^+e^- \rightarrow 2\gamma$, Pair Annihilation

4 Formal Developments

4.1 Optical Theorem

Lec. 16-17

The optical theorem is a consequence of the unitarity of the S-matrix. We have,

$$S = 1 + iT \implies S^\dagger S = 1 = (1 - iT^\dagger)(1 + iT) \implies -i(T - T^\dagger) = T^\dagger T. \quad (4.1)$$

This allows us to write, for forward scattering,

$$\begin{aligned} \langle \mathbf{k}_1 \mathbf{k}_2 | T^\dagger T | \mathbf{k}_1 \mathbf{k}_2 \rangle &= \sum_n \left(\prod_{i=1}^n \int \frac{d^3 q_i}{(2\pi)^3 2E_i} |\langle \mathbf{k}_1 \mathbf{k}_2 | T^\dagger | \{\mathbf{q}_i\} \rangle|^2 \right) \\ \implies \text{Im } \mathcal{M}(k_1, k_2 \rightarrow k_1, k_2) &= 2E_{\text{cm}} p_{\text{cm}} \sigma_{\text{tot}}(k_1, k_2 \rightarrow \text{anything}). \end{aligned}$$

Example. Consider a creation process $m_1 + m_2 \rightarrow m_3$. There is a pole at $s^2 - m_3^2$. This is known as **resonance production**. Similarly, **branch cuts** correspond to 2-particle intermediate states. With the optical theorem,

$$A_{fi} - A_{if}^* = \frac{i}{64\pi^2} \sqrt{\frac{s - 4m^2}{s}} \theta(s - 4m^2) \int d\Omega \langle f | A | k_1 k_2 \rangle \langle k_1 k_2 | A | k \rangle.$$

It is clear that there is a square root branch cut starting at $s = 4m^2$. To work around branch cuts, it is necessary to use analytic continuation - if A_{fi} and A_{if}^* are equal on $\mathbb{R} \cap [s < 4m^2]$, they are equal everywhere except on singularities.:

$$A_{fi}(s) = A_{if}^*(s), \quad s < 4m^2 \implies A_{fi}(s) = A_{if}^*(s^*), \quad s > 4m^2.$$

Example. For forward scattering, $A(s) = A^*(s^*)$. For $s = s + i\epsilon$, this states $\text{Re } A(s + i\epsilon) + i \text{Im } A(s + i\epsilon) = \text{Re } A(s - i\epsilon) - i \text{Im } A(s - i\epsilon)$ - the real part is continuous while the imaginary part has a sign discontinuity, $\text{Disc } A = 2i \text{Im } A(s + i\epsilon)$. Because of this discontinuity, it is useful to use Feynman prescription, writing m^2 as $m^2 - i\epsilon$, which moves the branch cut to slightly under the real axis.

Method of dispersion relations makes use of poles and branch cuts on $A(s)$ along the real axis to reconstruct the amplitude. For a single branch cut (implying no crossing symmetries), by the Residue theorem, we get

$$\frac{1}{2\pi i} \oint \frac{f(z)}{z - z} dz = f(z) = \frac{1}{2\pi i} \int_0^\infty dx \frac{f(x + i\epsilon) - f(x - i\epsilon)}{x - z}.$$

Since the optical theorem relates Feynman diagrams of order λ^α to the imaginary part of $\lambda^{2\alpha}$, we can recursively use dispersion relation to get higher order terms.

4.2 Renormalization

Lec. 17-20 but will be using Burdman's notes⁹.

We define the **one part irreducible** diagram as a diagram that cannot be disconnected by cutting a single internal line. Then, a full propagator can be written as a geometric series of one part irreducibles:

$$\frac{i}{p^2 - m^2 + i\epsilon} + (-i\Pi(p^2)) \left(\frac{i}{p^2 - m^2 + i\epsilon} \right)^2 + (-i\Pi(p^2))^2 \left(\frac{i}{p^2 - m^2 + i\epsilon} \right)^3 + \dots = \frac{i}{p^2 - m^2 - \Pi(p^2) + i\epsilon}.$$

Example. Breit-Wigner resonance. First, consider the scattering amplitude $A(p^2) = \langle p | A | p \rangle$ of an unstable particle. It holds that

$$2i \text{Im } A(p^2) = i \int |\langle k_1 k_2 | A | p \rangle|^2 D^{(2)} d(k_1 k_2) \implies \text{Im } A(p^2) = m\Gamma.$$

Ignoring the real part of Π , we have $\text{Im } \Pi(p^2 = m^2) = -\text{Im } A(p^2 = m^2) = -m\Gamma$: the scattering amplitude can be written

$$A_{fi} \sim \frac{1}{2m(E_T - m) + im\Gamma} \implies \sigma \sim |A|^2 \sim \frac{1}{(E_T - m)^2 + \Gamma^2/4}$$

4.2.1 Mass Renormalization

We define the **physical mass** m to be where the pole is in the amplitude, as compared to the mass that appears in the Lagrangian, which we will call the bare mass m_0 . Therefore, we have

$$p^2 - m_0^2 - \Pi(p^2) \Big|_{p^2=m^2} = p^2 - m_0^2 - \left[\lambda^2 \Pi^{(2)}(p^2) + \lambda^3 \Pi^{(3)}(p^2) + \lambda^4 \Pi^{(4)} \dots \right] \Big|_{p^2=m^2} = 0,$$

where $-i\Pi^{(n)}$ is the 1 part irreducible scattering amplitude to the $\mathcal{O}(\lambda^n)$ order.

Evidently, $m^2 = m^2(m_0^2, \lambda)$. If we write

$$m_0^2 = m^2 + \delta m^2 = m^2 + \lambda^2 (\delta m^{(2)})^2 + \lambda^3 (\delta m^{(3)})^2 + \lambda^4 (\delta m^{(4)})^2 + \dots,$$

where δm^2 is the mass correction, we obtain

$$\mathcal{L} = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{m^2}{2} \phi^2 - \frac{\delta m^2}{2} \phi^2 + \mathcal{L}_{\text{int}}.$$

Hence, the effective interaction Lagrangian has a $\delta m^2/2\phi^2$ term, which we will call the **mass counterterm**.

⁹http://fma.if.usp.br/~%7Eburdman/QFT1/lecture_21.pdf

4.2.2 Field Renormalization

Writing the propagator,

$$\frac{i}{p^2 - m^2 - \Pi^{\text{full}}(p^2)} \sim \frac{i}{(p^2 - m^2)(1 - \Pi'(m^2))} \equiv \frac{iZ}{p^2 - m^2}, \quad z = \frac{1}{1 - \Pi'(m^2)} \sim 1 + \Pi'(m^2).$$

For the residue to stay constant, we need $\Pi'(m^2) = 0$.

From the optical theorem, we see that $\int d^4k Z |k\rangle \langle k| = \mathbb{1}$, requiring $\phi \rightarrow \frac{\phi_0}{\sqrt{Z}}$ for the external momenta to be properly normalized. For this, it is convenient to define $Z = 1 + \delta Z$.

4.3 Regularization

4.3.1 Momentum Cutoff

It is possible to evaluate how much an interaction diverges by introducing a cutoff momentum Λ to the integrals. The superficial degree of divergence of a ϕ^n theory in d dimensions is

$$D = dL - 2I, \quad nV = E + 2I, \quad L = I - (V - 1) \implies D = d \left(1 - \frac{1}{n}\right) E - 2 \left(1 + \frac{d}{n}\right) I + d,$$

where there are E external lines, V vertices, I internal lines, and L loops. Given D , we say

- $D > 0$: Super-renormalizable. In EFT, relevant;
- $D = 0$: Renormalizable. In EFT, marginally relevant;
- $D < 0$: Non-renormalizable. In EFT, irrelevant.

In EFT, we let the interaction constant λ be dimensionless and match higher order dimensions with cutoff scale Λ . In EFT, non-renormalizable operators are p^2/Λ^2 suppressed.

However, in this perspective, bare mass is given $m^2 = \Lambda^2 \lambda_2$ where λ_2 is dimensionless, which means m_0^2 is tuned to accuracy $m_{\text{phys}}^2/\Lambda^2$.

4.4 Loop Integrals

Lec. 21

4.4.1 Useful Formulae

Feynman parametrization is given as

$$\frac{1}{A_1 \cdots A_n} = \int_0^1 dx_1 \cdots dx_n \cdot \delta \left(\sum x_i - 1 \right) \frac{(n-1)!}{(x_1 A_1 + \cdots + x_n A_n)^n}. \quad (4.2)$$

For repeated elements, we have

$$\frac{1}{A_1^{m_1} A_2^{m_2} \cdots A_n^{m_n}} = \int_0^1 dx_1 \cdots dx_n \delta \left(\sum x_i - 1 \right) \frac{\prod x_i^{m_i-1}}{(x_1 A_1 + \cdots + x_n A_n)^{m_1 + \cdots + m_n}} \quad (4.3)$$

d dimensional volume element is given as (assuming isotropy)

$$d^d k = \Omega_{d-1} k^{d-1} dk = \frac{2\pi^{d/2}}{\Gamma(d/2)} k^{d-1} dk. \quad (4.4)$$

Example. ϕ^3 1-Loop Diagram. The one-loop integral for ϕ^3 theory is

$$\begin{aligned} iA &= \frac{1}{2} (-i\lambda)^2 \int_{\mathbb{R}^{1,3}} \frac{d^4 k}{(2\pi)^4} \frac{i}{k^2 - m^2 + i\epsilon} \frac{i}{(k-p)^2 - m^2 + i\epsilon} \\ &= \frac{\lambda^2}{2} \int_0^1 dx \int_{\mathbb{R}^{1,3}} \frac{d^4 k}{(2\pi)^4} \frac{1}{[(k^2 - m^2)(1-x) + x((k-p)^2 - m^2) + i\epsilon]^2} \\ &= \frac{\lambda^2}{2} \int_0^1 dx \int_{\mathbb{R}^{1,3}} \frac{d^4 k}{(2\pi)^4} \frac{1}{[k^2 - (m^2 - p^2 x(1-x)) + i\epsilon]^2} \\ &= \frac{i\lambda^2}{2} \int_0^1 dx \int_{\mathbb{R}^4} \frac{d^4 k}{(2\pi)^4} \frac{1}{[k^2 + a]^2}, \quad a = (m^2 - p^2 x(1-x)) \\ &= \frac{i\lambda^2}{16\pi^2} \int_0^1 dx \int_0^\Lambda dk \frac{k^2}{(k^2 + a - i\epsilon)^2} \\ &= \frac{i\lambda^2}{16\pi^2} \int_0^1 dx \left(\log \left(\frac{\Lambda^2}{a} \right) - 1 \right). \end{aligned}$$

5 Path Integral Formulation

5.1 Derivation

We claim that the propagation amplitude can be written as a functional integral of the exponent of the action:

$$U(x_a, x_b; T) = \int \mathcal{D}x(t) e^{iS[x(t)]/\hbar}. \quad (5.1)$$

In the classical limit ($S[x] \gg \hbar$), this makes sense because $\frac{\delta S[x(t)]}{\delta x(t)} = 0$ by the method of stationary phase, agreeing with the principle of least action.

In a more practical form, (5.1) can be written as

$$\begin{aligned} U(q_0, q_N; T) &= \left(\prod_{i,k} \int \frac{dq_k^i dq_k^i}{2\pi} \right) \exp \left[i \sum_{i,k} p_k^i (q_{k+1}^i - q_k^i) - \epsilon H \left(\frac{q_{k+1} + q_k}{2}, p_k \right) \right] \\ &= \left(\prod_i \int \mathcal{D}q(t) \mathcal{D}p(t) \right) \exp \left[i \int_0^T dt \left(\sum_i p^i \dot{q}^i - H(q, p) \right) \right]. \end{aligned} \quad (5.2)$$

5.2 Quantization of Scalar Fields

The correlation function, in terms of path integrals, is

$$\langle \Omega | T \phi_H(x_1) \phi_H(x_2) | \Omega \rangle = \lim_{T \rightarrow \infty (1-i\epsilon)} \frac{\int \mathcal{D}\phi \phi(x_1) \phi(x_2) \exp \left[i \int_{-T}^T d^4x \mathcal{L} \right]}{\int \mathcal{D}\phi \exp \left[i \int_{-T}^T d^4x \mathcal{L} \right]} \quad (5.3)$$

Consider a non-interacting real scalar field ($\mathcal{L}_0 = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m^2 \phi^2$). In the momentum space, defined

$$\phi(x_i) = \frac{1}{V} \sum_n e^{-ik_n \cdot x_i} \phi(k_n),$$

where the $n > 0$ comes from $\phi^*(k) = \phi(-k)$. The denominator can be written

$$\int \mathcal{D}\phi e^{iS_0} = \left(\prod_{k^0 > 0} \int d(\text{Re } \phi_n) d(\text{Im } \phi_n) \right) \exp \left[-\frac{i}{V} \sum_{k^0 > 0} (m^2 - k_n^2) |\phi_n|^2 \right] = \prod_{\text{all } k_n} \sqrt{\frac{i\pi V}{k_n^2 - m^2 + i\epsilon}}.$$

We can write our result using the **functional determinant**. Consider the integral

$$\left(\prod_k \int d\xi_k \right) \exp [-\xi_i B_{ij} \xi_j] \propto [\det B]^{-1/2}, \quad (5.4)$$

which allows us to write

$$\int \mathcal{D}\phi e^{iS_0} \propto [\det(m^2 + \partial^2)]^{-1/2}. \quad (5.5)$$

Similarly, the numerator can be written

$$\begin{aligned} \int \mathcal{D}\phi \phi(x_1) \phi(x_2) e^{iS_0} &= \frac{1}{V^2} \sum_{m,l} e^{-i(k_m \cdot x_1 + k_l \cdot x_2)} \left(\prod_{k_n^0 > 0} \int d(\text{Re } \phi_n) d(\text{Im } \phi_n) \right) \cdot (\text{Re } \phi_m + i \text{Im } \phi_m)(\text{Re } \phi_l + i \text{Im } \phi_l) \\ &\quad \cdot \exp \left[-\frac{i}{V} \sum_{k_n^0 > 0} (m^2 - k_n^2) [(\text{Re } \phi_n)^2 + (\text{Im } \phi_n)^2] \right] \\ &= \frac{1}{V^2} \sum_m e^{-ik_m \cdot (x_1 - x_2)} \left(\prod_{k_n^0 > 0} \frac{-i\pi V}{m^2 - k_n^2} \right) \frac{-iV}{m^2 - k_m^2 - i\epsilon}, \end{aligned}$$

where we have used the fact that unless $k_m = -k_l$, the integrand is odd ($k_m = k_l$ cancels Re^2 with Im^2).

Taking the continuum limit of the fraction, we obtain

$$\langle 0 | T \phi(x_1) \phi(x_2) | 0 \rangle = \int \frac{d^4k}{(2\pi)^4} \frac{i e^{-ik \cdot (x_1 - x_2)}}{k^2 - m^2 + i\epsilon}. \quad (5.6)$$

Similarly, the four-point function is nonzero for when two of its fields are equal but opposite in sign.

It is useful to consider the **generating functional** when computing the correlation functions. We define

$$Z[J] \equiv \int \mathcal{D}\phi \exp \left[i \int d^4x [\mathcal{L} + J(x)\phi(x)] \right]. \quad (5.7)$$

The two-point function is simply

$$\langle 0 | T \phi(x_1) \phi(x_2) | 0 \rangle = \frac{1}{Z[J=0]} \left(\frac{1}{i^2} \frac{\delta^2}{\delta J(x_1) \delta J(x_2)} \right) Z[J] \Big|_{J=0}, \quad (5.8)$$

from (5.3).

For the free scalar field theory, we can explicitly find the generating functional.

$$\begin{aligned} Z[J] &\equiv \int \mathcal{D}\phi \exp \left[i \int d^4x \left[\frac{1}{2} \phi(-\partial^2 - m^2 + i\epsilon) \phi + J(x)\phi(x) \right] \right] \\ &= \int \mathcal{D}\phi' \exp \left[i \int d^4x \left[\frac{1}{2} \phi'(-\partial^2 - m^2 + i\epsilon) \phi' - \frac{1}{2} J(-\partial^2 - m^2 + i\epsilon)^{-1} J \right] \right] \\ &= Z_0 \exp \left[-\frac{1}{2} \int d^4x \int d^4y J(y) D_F(y-x) J(x) \right] \end{aligned}$$

where $\phi' = \phi + (-\partial^2 - m^2 + i\epsilon)^{-1}J$. Note that to compute $(-\partial^2 - m^2 + i\epsilon)^{-1}$ we need to work in the momentum space. The four-point function is then

$$\begin{aligned}
\langle 0|T\phi(x_1)\phi(x_2)\phi(x_3)\phi(x_4)|0\rangle &= \frac{1}{Z_0} \prod_{j=1}^4 \left(\frac{1}{i} \frac{\delta}{\delta J(x_j)} \right) e^{-\frac{1}{2}J_x D_{xy} J_y} \\
&= \frac{1}{Z_0} \prod_{j=1}^3 \left(\frac{1}{i} \frac{\delta}{\delta J(x_j)} \right) \left(-J_x D_{x4} e^{-\frac{1}{2}J_x D_{xy} J_y} \right) \\
&= \frac{1}{Z_0} \prod_{i=1}^2 \left(\frac{1}{i} \frac{\delta}{\delta J(x_j)} \right) \left((-D_{34} + J_x D_{x4} J_y D_{y3}) e^{-\frac{1}{2}J_x D_{xy} J_y} \right) \\
&= \frac{1}{Z_0} \prod_{j=1}^1 \left(\frac{1}{i} \frac{\delta}{\delta J(x_j)} \right) \left((J_x D_{x2} D_{34} + D_{24} J_y D_{y3} + J_x D_{x4} D_{23}) e^{-\frac{1}{2}J_x D_{xy} J_y} \right) \\
&= (D_{12} D_{34} + D_{24} D_{13} + D_{14} D_{23}).
\end{aligned}$$

5.3 Quantization of EM Field

The functional integral for the electromagnetic theory is

$$\int \mathcal{D}A e^{iS[A]}, \quad S = \int d^4x \left[-\frac{1}{4}(F_{\mu\nu})^2 \right] = \frac{1}{2} \int d^4x A_\mu (\partial^2 g^{\mu\nu} - \partial^\mu \partial^\nu) A_\nu.$$

This expression vanishes if $\tilde{A}_\mu = k_\mu \alpha(k)$ for any scalar function $\alpha(k)$, meaning the path integral is badly divergent.

Let $G(A) = 0$ be a gauge-fixing condition; for example, $G(A) = \partial_\mu A^\mu$ for Lorentz gauge. We consider the identity

$$1 = \int \mathcal{D}\alpha(x) \delta(G(A^\alpha)) \det \left(\frac{\delta G(A^\alpha)}{\delta \alpha} \right), \quad A_\mu^\alpha(x) = A_\mu(x) + \frac{1}{e} \partial_\mu \alpha(x). \quad (5.9)$$

Note that $\det \left(\frac{\delta G(A^\alpha)}{\delta \alpha} \right) = \det \left(\frac{\partial^2}{e} \right)$ is constant. With this condition, the functional integral becomes

$$\int \mathcal{D}A e^{iS[A]} = \det \left(\frac{\delta G(A^\alpha)}{\delta \alpha} \right) \int \mathcal{D}\alpha \int \mathcal{D}A e^{iS[A]} \delta(G(A)), \quad (5.10)$$

where we have used the gauge invariance of S and the fact that $A \rightarrow A^\alpha$ is a simple shift. Consider letting $G(A) = \partial^\mu A_\mu(x) - \omega(x)$ for a generalization of the Lorentz gauge condition and integrate over all $\omega(x)$ with a weighting function:

$$\begin{aligned}
\int \mathcal{D}A e^{iS[A]} &= N(\xi) \int \mathcal{D}\omega \exp \left[-i \int d^4x \frac{\omega^2}{2\xi} \right] \det \left(\frac{1}{e} \partial^2 \right) (\mathcal{D}\alpha) \int \mathcal{D}A e^{iS[A]} \delta(\partial^\mu A_\mu - \omega(x)) \\
&= N(\xi) \det \left(\frac{1}{e} \partial^2 \right) \left(\int \mathcal{D}\alpha \right) \int \mathcal{D}A e^{iS[A]} \exp \left[-i \int d^4x \frac{1}{2\xi} (\partial^\mu A_\mu)^2 \right].
\end{aligned}$$

Hence, the correlation function is

$$\langle \Omega | T\mathcal{O}(A) | \Omega \rangle = \lim_{T \rightarrow \inf(1-i\epsilon)} \frac{\int \mathcal{D}A \mathcal{O}(A) \exp \left[i \int_{-T}^T d^4x \left[\mathcal{L} - \frac{1}{2\xi} (\partial^\mu A_\mu)^2 \right] \right]}{\int \mathcal{D}A \exp \left[i \int_{-T}^T d^4x \left[\mathcal{L} - \frac{1}{2\xi} (\partial^\mu A_\mu)^2 \right] \right]}. \quad (5.11)$$

The photon propagator is

$$\tilde{D}_F^{\mu\nu}(k) = -\frac{i}{k^2 + i\epsilon} \left(g^{\mu\nu} - (1 - \xi) \frac{k^\mu k^\nu}{k^2} \right). \quad (5.12)$$