

University of Oslo

FYS4170/9170 — Relativistic Quantum Field Theory

Problem set 5

Problem 1 Classical field theory for the Dirac field

(J. Skaar)

The Lagrangian for the Dirac field is

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi. \quad (1)$$

Here $\psi = \psi(x)$ is a wave function object consisting of 4 elements, $\bar{\psi} = \psi^\dagger\gamma_0$, and γ^μ for $\mu = 0, 1, 2, 3$ are constant 4×4 matrices. Note that while μ is a spacetime index, the four elements ψ_α of ψ do not correspond to the four dimensions of spacetime.

a) Argue that (1) can be written in the form

$$\mathcal{L} = \bar{\psi}_\alpha i\gamma^\mu_{\alpha\beta} \partial_\mu \psi_\beta - m \bar{\psi}_\alpha \psi_\alpha, \quad (2)$$

where we have used the Einstein summation convention, and the indices α and β run over the four elements of the vectors.

b) Find the Euler-Lagrange equation for ψ and $\bar{\psi}$ by treating ψ and $\bar{\psi}$ (or $\psi^\dagger$) as independent.

c) The Lagrangian is unchanged under a global phase transformation

$$\psi(x) \rightarrow e^{-i\alpha}\psi(x), \quad (3)$$

where the constant α is real. What is the associated, conserved Noether current density?

Problem 2 Dirac matrices (L. L. Braseth, T. Klungland)

This problem is intended to give you some practice working with Dirac matrices, as well as to show the origin of some identities that will be very useful in future calculations.

All of the identities can be found from the Dirac algebra,

$$\{\gamma^\mu, \gamma^\nu\} = 2g^{\mu\nu}\mathbb{1}_{4\times 4}. \quad (4)$$

Note that the identity matrix on the right-hand side is usually left implicit, but in certain situations (for example in part b) it is important to remember that it is there.

a) Show the following contraction identities:

$$\gamma^\mu\gamma_\mu = 4, \quad (5)$$

$$\gamma^\mu\gamma^\nu\gamma_\mu = -2\gamma^\nu, \quad (6)$$

$$\gamma^\mu\gamma^\nu\gamma^\alpha\gamma_\mu = 4g^{\nu\alpha}, \quad (7)$$

$$\gamma^\mu\gamma^\nu\gamma^\alpha\gamma^\rho\gamma_\mu = -2\gamma^\rho\gamma^\alpha\gamma^\nu. \quad (8)$$

b) Calculations involving fermions typically involve evaluating traces of Dirac matrices, and products of such. These calculations can be sped up substantially by recalling some properties of these traces; to that end, derive the following relations by using the Dirac algebra and the cyclic property of traces, $\text{Tr}(ABC) = \text{Tr}(CAB)$. For the last identity, the γ^5 matrix $\gamma^5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3$, which satisfies $(\gamma^5)^2 = \mathbb{1}_{4 \times 4}$, $\{\gamma^5, \gamma^\mu\} = 0$, may be useful.

$$\text{Tr}[\gamma^\mu \gamma^\nu] = 4g^{\mu\nu}, \quad (9)$$

$$\text{Tr}[\gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma] = 4g^{\mu\nu}g^{\rho\sigma} - 4g^{\mu\rho}g^{\nu\sigma} + 4g^{\mu\sigma}g^{\nu\rho}, \quad (10)$$

$$\text{Tr}[\gamma^{\mu_1} \dots \gamma^{\mu_n}] = 0, \text{ for } n = 2m - 1 \text{ (odd)}. \quad (11)$$

c) Show the following identities involving contractions between Dirac matrices and four-momenta, $p_\mu \gamma^\mu \equiv \not{p}$:

$$(\not{p})^2 = p^2, \quad (12)$$

$$\text{Tr}[\not{p}_1 \not{p}_2 \not{p}_3 \not{p}_4] = 4(p_1 \cdot p_2)(p_3 \cdot p_4) - 4(p_1 \cdot p_3)(p_2 \cdot p_4) + 4(p_1 \cdot p_4)(p_2 \cdot p_3). \quad (13)$$

Problem 3 Classical source of particles (J. Skaar)

In this problem we will consider the creation of Klein-Gordon particles with a classical current source $j(x)$, see P&S p. 32. The creation of photons with a classical, electric current source will be similar.

Recall that $\tilde{j}(p)$ is the Fourier transform of $j(x)$, and that the Heisenberg-picture field transforms from its usual free form

$$\phi_{\text{free}}(x) = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\sqrt{2E_{\mathbf{p}}}} \left\{ a_{\mathbf{p}} e^{-ipx} + \text{h.c.} \right\} \quad (14)$$

to

$$\phi(x) = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\sqrt{2E_{\mathbf{p}}}} \left\{ [a_{\mathbf{p}} + \alpha \psi(\mathbf{p})] e^{-ipx} + \text{h.c.} \right\} \quad (15)$$

by the action of the source. Here

$$\alpha \psi(\mathbf{p}) = \frac{i}{\sqrt{2E_{\mathbf{p}}}} \tilde{j}(p), \quad (16)$$

where $p^2 = m^2$. The parameter α is included such that $\psi(\mathbf{p})$ can be assumed normalized: $\int \frac{d^3p}{(2\pi)^3} |\psi(\mathbf{p})|^2 = 1$.

You may find the following operator identity useful:

$$e^A B e^{-A} = B + [A, B] + \frac{1}{2!} [A, [A, B]] + \dots \quad (17)$$

In addition you may need the Baker–Campbell–Hausdorff formula:

$$e^A e^B = e^C, \text{ where } C = A + B + \frac{1}{2} [A, B] + \frac{1}{12} [A, [A, B]] - \frac{1}{12} [B, [A, B]] + \dots \quad (18)$$

a) Define the wavepacket ladder operator

$$a_{\psi}^{\dagger} = \int \frac{d^3p}{(2\pi)^3} \psi(\mathbf{p}) a_{\mathbf{p}}^{\dagger}, \quad (19)$$

and a so-called displacement operator

$$D(\alpha) = e^{\alpha a_{\psi}^{\dagger} - \alpha^* a_{\psi}} \quad (20)$$

Note that $D(\alpha)$ is unitary, and show that

$$D^{\dagger}(\alpha) a_{\mathbf{p}} D(\alpha) = a_{\mathbf{p}} + \alpha \psi(\mathbf{p}). \quad (21)$$

b) Eq. (21) implies that

$$\phi(x) = D^{\dagger}(\alpha) \phi_{\text{free}}(x) D(\alpha). \quad (22)$$

Thus the unitary source operator (or time-evolution operator) in the Heisenberg picture is $D(\alpha)$.

Going to the Schrödinger picture, describe the action of the source if we start in a vacuum state. Prove that the resulting state is a coherent state,

$$|\alpha\rangle_{\psi} = e^{-|\alpha|^2/2} \sum_n \frac{(\alpha a_{\psi}^{\dagger})^n}{n!} |0\rangle = e^{-|\alpha|^2/2} \sum_n \frac{\alpha^n}{\sqrt{n!}} |n\rangle_{\psi}. \quad (23)$$

Here $|n\rangle_{\psi}$ denotes a n -photon state in the wavepacket ψ . This result is perhaps not very surprising; a classical source produces a classical (coherent) state. For photons this is an expected result: The electromagnetic state produced by a current (an antenna) is a coherent state, which describes a classical electromagnetic field.