

**Physics 582, Fall Semester 2023**  
**Professor Eduardo Fradkin**

**Problem Set No. 2:**  
**Symmetries and Conservation Laws**  
**Due Date: Friday September 22, 2023,**  
**9:00 pm US Central Time**

Here you will look again at problem 5 of Problem Set 1 in which you studied some of the properties of the dynamics of a *charged* (complex) scalar field  $\phi(x)$  coupled to the electromagnetic field  $A_\mu(x)$ . Recall that the Lagrangian density  $\mathcal{L}$  for this system is

$$\mathcal{L} = (D_\mu \phi(x))^* (D^\mu \phi(x)) - m_0^2 |\phi(x)|^2 - \frac{\lambda}{2} (|\phi(x)|^2)^2 - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \quad (1)$$

where  $D_\mu$  is the *covariant derivative*

$$D_\mu \equiv \partial_\mu + ieA_\mu \quad (2)$$

$e$  is the electric charge and  $*$  denotes complex conjugation. In this problem set you will determine several important properties of this field theory at the classical level.

1. Derive an expression for the *locally conserved current*  $j_\mu(x)$ , associated with the *global* symmetry

$$\begin{aligned} \phi(x) &\rightarrow \phi'(x) = e^{i\theta} \phi(x) \\ \phi^*(x) &\rightarrow \phi'^*(x) = e^{-i\theta} \phi^*(x) \\ A_\mu(x) &\rightarrow A'_\mu(x) = A_\mu(x) \end{aligned} \quad (3)$$

in terms of the fields of the theory.

2. Show that the conservation of the current  $j_\mu$  implies the existence of a *constant of motion*. Find an explicit form for this constant of motion.
3. Consider now the case of the *local (gauge)* transformation

$$\begin{aligned} \phi(x) &\rightarrow \phi'(x) = e^{i\theta(x)} \phi(x) \\ \phi^*(x) &\rightarrow \phi'^*(x) = e^{-i\theta(x)} \phi^*(x) \\ A_\mu(x) &\rightarrow A'_\mu(x) = A_\mu(x) + \partial_\mu \Lambda(x) \end{aligned} \quad (4)$$

where  $\theta(x)$  and  $\Lambda(x)$  are two functions. What should be the relation between  $\theta(x)$  and  $\Lambda(x)$  for this transformation to be a symmetry of the Lagrangian of the system?

4. Show that, if the system has the local symmetry of the previous section, there is a locally conserved *gauge current*  $J_\mu(x)$ . Find an explicit expression for  $J_\mu$  and discuss in which way it is different from the current  $j_\mu$  of item 1). Find an explicit expression for the associated constant of motion and discuss its physical meaning.
5. Find the Energy-Momentum  $T^{\mu\nu}$  tensor for this system. Show that it can be written as the sum of two terms

$$T^{\mu\nu} = T^{\mu\nu}(A) + T^{\mu\nu}(\phi, A) \quad (5)$$

where  $T^{\mu\nu}(A)$  is the energy-momentum tensor for the free electromagnetic field and  $T^{\mu\nu}(\phi, A)$  is the tensor which results by modifying the energy-momentum tensor for the decoupled complex scalar field  $\phi$  by the *minimal coupling* procedure.

6. Find explicit expressions for the Hamiltonian density  $\mathcal{H}(x)$  and the linear momentum density  $\mathcal{P}(x)$  for this system. Give a physical interpretation for all of the terms that you found for each quantity.
7. Consider now the case of an infinitesimal Lorentz transformation

$$x_\mu \rightarrow x'_\mu + \omega_{\mu\nu} x^\nu \quad (6)$$

where  $\omega_{\mu\nu}$  infinitesimal and antisymmetric. Show that the invariance of the Lagrangian of this system under these Lorentz transformation leads to the existence of a conserved tensor  $M_{\mu\nu\lambda}$ . Find the explicit form of this tensor. Give a physical interpretation for its *spacial* components. Does the conservation of this tensor impose any restriction on the properties of the energy-momentum tensor  $T^{\mu\nu}$ ? Explain.

**Warning:** Be very careful in how you treat the fields. Recall that *not all* of the fields are scalars!

8. In this section yo will consider again the same system but in a *polar* representation for the scalar field  $\phi$ , i.e.

$$\phi(x) = \rho(x) e^{i\omega(x)} \quad (7)$$

In problem set 1, problem 2, you showed that for  $m_0^2 < 0$  the lowest energy states of the system can be well approximated by freezing the amplitude mode  $\rho$  to a constant value  $\rho_0$  which you obtained by an energy minimization argument. In this section you are asked to find the form of

- (a) the conserved gauge current  $J_\mu$ ,
- (b) the total energy  $H$ ,
- (c) the total linear momentum  $\mathbf{P}$  in this limit.

9. Consider now the analytic continuation to imaginary time of this theory. Find the energy functional of the equivalent system in classical statistical mechanics. Give a physical interpretation for each of the terms of this energy functional. If  $D$  is the dimensionality of *space-time* for the original system, what is the dimensionality of *space* for the equivalent classical problem?

**Warning** : Be very careful in the way you perform the analytic continuation of the components of the vector potential.