

# Physics 6820 – Homework 3

(Dated: Due: September 13, 2019)

## 1. Maxwell's equations. [32 points]

In this problem, we consider the action for some particles and the electromagnetic field in special relativity:

$$S = \sum_{\text{particles}} \left[ -m \int d\tau + q \int A_\mu(\mathbf{x}) dx^\mu \right] + \int -\frac{1}{4} F_{\gamma\mu} F^{\gamma\mu} d^4\mathbf{x}. \quad (1)$$

Here  $\mathbf{A}$  is a 1-form, and in the sum over particles,  $m$  is the mass of the particle and  $q$  is its electric charge. The 2-form electromagnetic field tensor is  $\mathbf{F} = d\tilde{\mathbf{A}}$ . We have used units where  $\epsilon_0 = 1$  (and since  $c = 1$ , we will also have  $\mu_0 = 1$ ).

On Homework #2, you showed that the particle acceleration satisfied  $ma_\gamma = qF_{\gamma\mu}u^\mu$ , and that the field components were

$$F_{\gamma\mu} \rightarrow \left( \begin{array}{c|ccc} 0 & -E_x & -E_y & -E_z \\ \hline E_x & 0 & B_z & -B_y \\ E_y & -B_z & 0 & B_x \\ E_z & B_y & -B_x & 0 \end{array} \right). \quad (2)$$

(a) [4 points] Show that the  $\sum_{\text{particles}} q \int A_\mu(\mathbf{x}) dx^\mu$  term in the action can be written as

$$\int A_\mu J^\mu d^4\mathbf{x}, \quad (3)$$

where the 4-current density  $\mathbf{J}$  for a swarm of particles is:

$$J^\mu(\mathbf{y}) = \sum_{\text{particles}} q \int \delta^{(4)}(\mathbf{x}(\sigma) - \mathbf{y}) \frac{dx^\mu(\sigma)}{d\sigma} d\sigma. \quad (4)$$

(b) [3 points] Explain (maybe with words and a few equations) why  $J^0$  is the usual charge density and  $J^i$  are the components of the usual current density.

(c) [6 points] Now let's consider the variation  $\delta S$  of the action to first order when there is a small change  $\delta A_\mu$  in the 4-vector potential. Show that

$$\delta S = \int (J^\mu \delta A_\mu - F^{\gamma\mu} \partial_\gamma \delta A_\mu) d^4\mathbf{x}. \quad (5)$$

Conclude, using integration by parts, that the equation of motion is

$$-F^{\gamma\mu}{}_{,\gamma} = J^\mu. \quad (6)$$

(d) [4 points] By explicitly writing the components, show that the equations of motion from (c) correspond to Gauss's law and to Ampère's law (including displacement current).

(e) [4 points] Explain why the 3-form  $\tilde{d}\mathbf{F} = 0$ . Show that the 4 independent components of this equation correspond to the divergencelessness of the magnetic field and to Faraday's law of induction.

(f) [4 points] Show that the equation of motion from (c) can be written in terms of differential forms as:

$$\tilde{d}(\star \mathbf{F}) = -\star \mathbf{J}. \quad (7)$$

What type of form is on both sides of this equation?

(g) [3 points] Show that the equation of motion in (f) *requires* that the 4-divergence of  $\mathbf{J}$  be zero. This is known as “automatic conservation of the source,” and will occur in GR as well. Express this equation both as a differential form and in index notation.

(h) [4 points] Show that the field part of the action (Eq. 1) can be written as

$$S = \int_{\mathbb{R}^4} +\frac{1}{4} \mathbf{F} \wedge \star \mathbf{F}. \quad (8)$$

where  $\mathbb{R}^4$  is the 4-dimensional region over which we do the integral.