Proposed Problems:

E1. Show explicitly why we need 1/2 in the Majorana mass term

E2. Show that the most general mass term Lagrangian for a 4-component field

$$\mathcal{L}_{D+M} = -m_D \overline{\Psi_L}\, \Psi_R - a\, \overline{\Psi_L^c}\, \Psi_L - b\, \overline{\Psi_R^c}\, \Psi_R + h.c.$$

describes two Majorana particles with different masses. Discuss in what limit the 4-component Dirac formalism can be recovered.

E3. How many physical phases there are in the mixing matrix if neutrinos are Majorana particles?

Proposed Problems:

E4. Show that a Majorana mass matrix is, in general, a complex symmetric matrix that can be diagonalized by an orthogonal matrix.

E5. Show that neutrinoless double beta decay implies in Majorana neutrinos [Schechter and Valle PRD25, 2951 (1982)]

E6. Consider the two body decay $\pi^- \to \mu^- + \bar{\nu}_\mu$ at rest. Calculate the momentum p_i and energy E_i of mass m_i. as a function of the masses of the pion, the muon and m_i. Estimate, to first non-zero order in m_i, the difference between E_i and p_i. Can we assume the neutrinos produced in this decay have the same energy or momentum?

Proposed Problems:

E7. Show explicitly that the Majorana phases do not enter in the neutrino oscillation probabilities

E8. Show how we get the 1.27 factor in the probability

$$\mathbf{P_{e\mu}(L) = \sin^2 2\theta \, \sin^2 \left(1.27 \, \frac{\Delta m^2_{21}}{eV^2} \, \frac{L}{m} \, \frac{MeV}{E} \right)}$$

E9. Why neutrino oscillation might exhibit CP violation in matter even though they might conserve CP in vacuum?

Proposed Problems:

E10. Neutrinos and anti-neutrinos of all flavors are produced inside a Supernova. Discuss the level crossing diagrams for neutrinos and anti-neutrinos for the normal and inverse mass hierarchy. Show there is a low and a high resonance and estimate the matter density at the these two resonance points.