Instructions: The exam is closed book and timed (50 minutes), so pace yourself. Problems will be graded on both technique and answer, so show your work. Credit will be awarded for later parts of a question even if the first part was answered incorrect. A formula sheet is on the last page.

**Part I—Short Answer**

[5 pts] 1. a) Describe one experiment that demonstrated the particle-like nature of a classical wave. Justify the interpretation of this experiment.

[5 pts] 2. a) How can identifying an electron as a wave result in quantization of energy?

[3 pts] 2. b) Why do classical electromagnetic waves not have quantized energy levels?

[3 pts] 3. b) Describe one experiment that demonstrated the wave-like nature of a classical particle. Again, justify the interpretation.

[4 pts] 3. List two principles which regard energy and time as conjugate variables. What is another conjugate pair? [bonus: What is a third?]

[4 pts] 4. In what aspects do both light and matter behave as particles, and in what aspects do they behave as waves?
5. List two aspects of the wavefunction \( \Psi(x, t) \) which embody its particle-like nature? How does this relate to the Heisenberg uncertainty principle?

6. Compare and contrast the cathode ray tube, the photoelectric effect, and X-ray tube.

7. Separate Plank’s law into two parts \( u(\nu)d\nu = g(\nu)d\nu \cdot \bar{\epsilon} \), and explain the general properties of each factor. What was the classical formula? In what limit are they equal? Explain in terms of energy levels how Plank’s new assumption solved the ultraviolet catastrophe.

Part II—Calculation

8. The luminosity (total power radiated) of the sun is \( 3.85 \times 10^{26} \) W. What is the surface temperature of the sun? \( r = 6.955 \times 10^8 \) m) What is the most intense wavelength of sunlight?

9. Given \( E = p^2/2m \), derive the dispersion relationship for \( w(k) \) \( [w \text{ as a function of } k] \). Calculate the group and phase velocities for such a particle as a function of \( w \) and/or \( k \).