1. An electron is initially at rest in a uniform electric field \( E \) in the negative y direction and a uniform magnetic field \( B \) in the negative z direction.
   a. Solve the equations of motion given by the Lorentz force
   b. Show that \( x(t) \) and \( y(t) \) satisfy the constraint equation \((x - \omega R t)^2 + (y - R)^2 = R^2\), where \( \omega = (eB/\hbar c) \).
   c. Sketch the path of the electron in the x-y plane for several cycles of the motion for \( B >> E \), \( B \sim E \), and \( B << E \).

2. For a molecule such as CO, which has a permanent electric dipole moment, radiative transitions obeying the selection rule \( \Delta l = \pm 1 \) between two rotation energy levels of the same vibrational energy state are allowed. (that is, the selection rule \( \Delta \nu = \pm 1 \) does not hold.)
   a. Find the moment of inertia of CO for which \( r_0 = 0.113 \) nm, and calculate the characteristic rotation energy \( E_{\text{rot}} \), in electron volts?
   b. Make an energy-level diagram for the rotational levels \( l=0 \) to \( l=5 \) for some vibrational level.
   c. Indicate on your diagram transitions that obey \( \Delta l = -1 \) and calculate the energy of the photons emitted.
   d. Find the wavelength of the photon emitted for each transition in (c). In what region of the electromagnetic spectrum are these photons?

3. Recently, 2000 rubidium atoms \( ^{87}_{37} \text{Rb} \), which had been compressed to a density of \( 10^{13} \) atoms/cm\(^3\), were observed to undergo a Bose-Einstein condensation as a function of temperature. This occurs when the de Broglie wavelengths overlap and the system forms a single macroscopic quantum state.
   a. Estimate the temperature at which Bose-Einstein condensation occurs for this system.
   b. The rubidium atoms are sufficiently far apart that they can be treated as non-interacting particles in a box. Estimate the transition energy from the ground state to the first excited state.

4. One of the strongest emission lines observed from distant galaxies comes from hydrogen and has a wavelength of 122 nm (in the ultraviolet region).
   a. How fast must a galaxy be moving away from us in order for that line to be observed in the visible region at 366 nm?
   b. What would be the wavelength of the line if that galaxy were moving toward us at the same speed?

5. A hypothetical atom has only two excited states, at 4.0 and 7.0 eV, and has a ground-state ionization energy of 9.0 eV. If we used a vapor of such atoms for the Franck-Hertz experiment, for what voltages would we expect to see decreases in the current? List all voltages up to 20V.

6. If an electron, initially at rest, is accelerated through a potential difference of 180kV.
   a. Calculate the total relativistic energy of the electron.
   b. Calculate the relativistic mass of the electron.
7. A typical particle production process is 
\[ p + p \rightarrow p + p + \pi^0. \]

Mass of proton = 938 MeV/c\(^2\); Mass of \( \pi^0 \) = 135 MeV/c\(^2\)

a. In a standard accelerator one of the initial protons would be at rest. In this case what is the minimum laboratory energy for the moving proton so that the reaction listed above occurs.

b. In colliding beam accelerators, such as the one proposed for the Superconducting Supercollider, the two initial particles are moving toward each other with equal speeds. Why do colliding beam accelerators have an energetic advantage over the type of accelerator described in part a of this question?

c. What energy would be required of each proton in a colliding beams accelerator to produce a pion?

8. A slab of lead shielding 1.0 cm thick reduces the intensity of 15 MeV \( \gamma \) rays by a factor of 2.

a. By what factor will 5.0 cm of lead reduce the beam?

b. What is the assumption cross-section for 15 MeV \( \gamma \)'s in lead nuclei? Lead has a density of 11.4 g/cm\(^3\), and an atomic weight of 207 g/mol.

9. Ordinary potassium contains 0.012 percent of the naturally occurring radioactive isotope \(^{40}\)K, which has a half-life of \( 1.3 \times 10^9 \) years.

a. What is the activity (decays/sec) of 1.0 kg of ordinary potassium?

b. What would have been the fraction of \(^{40}\)K in ordinary potassium \( 4.5 \times 10^9 \) years ago?

10. When sodium metal is illuminated with light of wavelength \( 4.20 \times 10^2 \) nm, the stopping potential is found to be 0.65 V; when the wavelength is changed to \( 3.10 \times 10^2 \) nm, the stopping potential is 1.69 V. Using only these data and the values of the speed of light and the electronic charge, find the work function of sodium and a value of Planck's constant.

11. A particular pair is produced such that the positron is at rest and the electron has a kinetic energy of 1.0 MeV moving in the direction of flight of the pair-producing photon.

a. Neglecting the energy transferred to the nucleus of the nearby atom, find the energy of the incident photon.

b. What percentage of the photons momentum is transferred to the nucleus.

c. What is the kinetic energy of the electron, as measured in the rest frame of the rocket?

d. What is the kinetic energy of the electron, as measured in the rest frame of the earth observer?

12. In HCl a number of absorption lines with wave numbers (in cm\(^{-1}\)) 83.03, 103.73, 124.30, 145.03, 165.51, 185.86 have been observed.

a. Carefully justify whether or not these transitions are vibrational or rotational transitions.

b. If these transitions represent vibrational transitions, determine the characteristic frequency and effective "spring" constant. If these transitions represent rotational transitions determine the J values, moment of inertia of HCl and separation distance between the nuclei.

13. The measured conductivity of copper at room temperature is 5.88x10\(^7\) \( \Omega^{-1} \)m\(^{-1}\), its Fermi energy is 7.03 eV, density is 8.96 gm/cm\(^3\) and molar mass is 63.5 gm/mole.

a. Calculate the density of free electrons in copper.

b. Calculate the average time between collisions of the conduction electrons.
c. Calculate the mean free path of electrons in copper.
d. Calculate the smallest possible de Broglie wavelength of electrons in copper at \(T = 0\)K. How does this value compare with the atomic separation in copper?

14. a. Make a diagram illustrating the split of the energy levels in the normal Zeeman effect for the states s, p and d of a spinless hydrogen atom (i.e., ignore electron spin in working this problem, even though in real life it is important).

b. By considering relevant selection rules, show on the diagram which transitions would occur and in a separate diagram the spectrum you would expect to see for the Balmer alpha (3 to 2) transition when it is Zeeman-split.

c. If such an atom is in a magnetic field of strength 5 kgauss (0.5 Tesla), estimate the wavelength and the fractional splitting of the levels for this line (i.e., put a quantitative scale on the spectrum diagram you drew in part c).

15. A linear symmetric triatomic molecule can have both rotational and vibrational energy levels.

a. Calculate the energy levels for the rotational states and sketch.

b. Sketch the normal vibrational modes of the molecule.

c. If the molecule is CO\(_2\) and has an internuclear distance of \(\sim 1.8\)Å, how many rotational states are excited at room temperature?.

16. Since the neutron has no charge, its mass must be found indirectly. From the data given below determine the mass difference \(m_n - m_H\). It might not be necessary to use all of the information provided.

a. \(^2\)H + \(^2\)H \(\rightarrow\) \(^3\)H + \(^1\)H + 4.031 MeV

b. \(^1\)H + n \(\rightarrow\) \(^2\)H + \(\gamma\), \(E\gamma = 2.225\) MeV

c. \(^3\)H \(\rightarrow\) \(^3\)He + e + 0.0185 MeV

d. \(^2\)H + \(^3\)H \(\rightarrow\) \(^3\)He + n + 3.267 MeV

17. In a double-slit interference experiment using helium atoms, the beam has atoms of kinetic energy 0.020 eV. The distance from the double slits to the observation plane is 64 cm.

a. What is the de Broglie wavelength of a helium atom with this kinetic energy?

b. What separation between the double slits is needed to produce interferences fringes separated by 10 \(\mu\)m at the observation plane?

18. A K\(^0\) meson (mass 497.7 MeV/c\(^2\)) decays to a \(\pi^+\), \(\pi^-\) meson pair with a mean life of 0.89 \(\times 10^{-10}\) s.

a. Which one of the fundamental interactions is responsible for this decay?

b. Suppose the K\(^0\) has a kinetic energy of 276 MeV when it decays, and that the two \(\pi\) mesons emerge at equal angles to the original K\(^0\) direction. Find the kinetic energy of each \(\pi\) meson and the opening angle between them. The mass of a \(\pi\) meson is 139.6 MeV/c\(^2\).

19. Compute the recoil proton kinetic energy (in MeV) in neutron beta decay: (a) when the electron has its maximum energy; (b) when the neutrino has its maximum energy. Proton mass \(M_p = 938.27\) MeV/c\(^2\), neutron mass \(M_n = 939.57\) MeV/c\(^2\), electron mass \(M_e = 0.5110\) MeV/c\(^2\).

20. The atomic number of Na is 11.

a. Write down the electronic configuration for the ground state of the Na atom showing in standard notation the assignment of all electrons to various one-electron states.

b. Give the standard spectroscopic notation for the ground state of the Na atom.
c. The lowest frequency line in the absorption spectrum of Na is a doublet. What are the spectroscopic designations of the pair of energy levels to which the atom is excited as a result of this absorption process?
d. Discuss the mechanism responsible for the splitting between this pair of energy level.
e. Which of these levels lies lowest? Discuss the basis on which you base your choice.

21. A gaseous discharge tube emits radiation lines which are identified as the $3P_{1/2} - 3S_{1/2}$ and $3P_{3/2} - 3S_{1/2}$ transitions. If the discharge tube is placed in a uniform weak magnetic field of magnitude $B$, the transitions are observed to split into several spectra lines. Make a level diagram with and without the magnetic field, and label the final levels and the transitions. Calculate the Landé $g$ factors, the level splittings, the resulting transition energies and the character of the radiation.

22. a. Sketch the energy level diagram for the $n = 2$ levels of atomic hydrogen. Include on your diagram the fine-structure splitting, the Lamb shift, and the hyperfine structure.
   b. Discuss the physical cause of each of the splittings listed above, and discuss the corresponding term in the Hamiltonian which causes the splitting.
   c. Estimate (order of magnitude) the size of each of these splittings.

23. A beam of protons, each with kinetic energy 40 MeV, approaches a step potential of 30 MeV.
   a. What fraction of the beam is reflected and transmitted?
   b. How does your answer change if the particles are electrons?

24. A shift of one fringe in the Michelson-Morley experiment corresponds to a change in the round-trip travel time along one arm of the interferometer by one period of vibration of light (about 2 femtosecond) when the apparatus is rotated by 90 degree. If ether existed, what velocity through the ether would be deduced from the shift of one fringe? (Take the length of the interferometer arm to be 10 m.)

25. A rocket with a proper length of 1000 m moves in the +x direction at a speed of 0.80c relative to an observer on earth. An astronaut standing at the rear of the rocket fires an electron (rest mass 0.51 MeV/c$^2$) toward the front of the rocket (through a vacuum pipe) at a speed of 0.90c relative to the rocket.
   a. How long a time does the electron take to reach the front of the rocket, as measured in the rest frame of the rocket?
   b. How long a time does the electron take to reach the front of the rocket, as measured in the rest frame of the earth observer?
   c. How long a time does the electron take to reach the front of the rocket, as measured in the rest frame of the earth observer?
   d. What is the kinetic energy of the electron, as measured in the rest frame of the rocket?
   e. What is the kinetic energy of the electron, as measured in the rest frame of the earth observer?

26. Three regions of scattered light are typically observed in Raman spectra.
   a. Explain what these three regions are. What is the physical reason for the appearance of inelastically-scattered components?
   b. Using the Boltzmann equation calculate the ratios of anti-Stokes to Stokes intensities at 20 °C and 40 °C for the Raman lines of CCl$_4$ molecule (218 cm$^{-1}$ and 459 cm$^{-1}$)
27. The sun is not only a strong source of photons, but is also a strong source of neutrinos.
a. What is the basic process for energy generation in the sun? Why does this process generate neutrinos? 
b. The flux of radiant energy (photons) from the sun striking the earth's atmosphere is 1350 W/m². Estimate the number of solar neutrinos which strike a square meter of the earth's surface every second. Justify any assumptions or approximations used in your estimate. The binding energy of helium 4 is 7.2 MeV per nucleon, and 1 eV = 1.6x10⁻¹⁹ J.

28. A π⁰-meson decays into two gamma ray photons with a lifetime of about 10⁻¹⁶ seconds. In the laboratory frame, the gamma ray photons have energies E₁ and E₂ and θ₁,2 is the angle between their directions. In terms of E₁, E₂ and θ₁,2, what is the rest mass of the π⁰?

29. An electron accelerated to 50 keV in an x-ray tube has two successive collisions in being brought to rest in the target, emitting two bremsstrahlung photons in the process. The second photon emitted has a wavelength 0.95 Å longer than the first.

a. What are the wavelengths of the two photons?
b. What was the energy of the electron after emission of the first photon?

30. X-ray photons of wavelength 0.02480 nm are incident on a target and the Compton-scattered photons are observed at 90.0°. (a) What is the wavelength of the scattered photons? (b) What is the momentum of the incident photons? Of the scattered photons? (c) What is the kinetic energy of the scattered electrons? (d) What is the momentum (magnitude and direction) of the scattered electrons?