Principles of Physics IV: Modern Physics

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Primary Textbook: Modern Physics by Tipler and Llewellyn
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1 Course Introduction

1. Kinematic assumptions originally stated that all items have a well-defined position that can be measured to any precision, and all observers agree on the time and position for a measurement
2. Newtonian mechanics were based on the idea of the deist clockwork universe
   (a) Conservation of momentum follows from Newton's third law, conservation of energy follows from the work energy theorm
   (b) Conservative forces have potential energy defined such that F = $-\nabla V$ (or U, depending on notation)
   (c) Newton's Laws combined with the fact that all known major forces act on the center of an object, implies conservation of angular momentum
3. Relativistic mechanics has $p = \gamma mv$ and $E^2 = c^2p^2 + m_0^2c^4$, and defined rigid bodies as impossible, often using the center of mass
4. Waves are travelling disturbances in a medium, averaged over space to consider bulk properties, carrying energy and momentum
   (a) Wave equations often relate curvature (second derivative w/ respect to x) to acceleration, $f_{xx} = (1/u^2)f_{tt}$ (u can be replaced with v, acting as an alternate velocity notation)
   (b) Waves are travelling, such that f(x, t) = g(x - ut)
   (c) y = exp(x - ct) is travelling, while sin(x)cos(ct) is a sum of two travelling, but not a travelling on its own, such that any g(x - ut) works
5. Waves but not particles can diffract, refract, and superposition, while both have velocity, generally localized position, momentum, and energy
   (a) Superposition creates nodes of no displacement, antinodes of max displacement in a standing wave
6. Maxwell's equations show that since changing magnetic fields produce electric fields and vice versa, waves can be created by oscillating or accelerating charges, travelling forever in vacuum

2 Chapter 3 - Quantization of Charge, Light, and Energy

1. In the 1800s, Faraday proved that a specific quantity of electricty could decompose one gram-ionic weight of monovalent ions, equal to a Faraday, or a mole of electrons, such that $Q = N_Ae$, called Faraday's Law of Electrolysis, displaying discrete electric charges
   (a) Zeeman later discovered that discrete spectral lines emitted by an atom in a magnetic field separate into three spaced lines of different frequencies, caused by the slightly different charge to mass ratios
      i. This proved that the particles producing the light were negative, and found the charge to mass ratio of the electrons
   (b) Thomsons cathode ray experiment later measured the same ratio as Zeeman, proving the existance of the electron, with the same ratio, as being the atomic negative component
      i. This combined with Faraday's charge allowed the mass of the electron to be determined
      ii. He also used a uniform magnetic field creating a circular path to measure the same ratio, found to be the same for all materials, showing it was universal for atoms
   (c) Millikan attempted to use a cloud of water droplets with a charge, such that Q = Ne, using the mass of the cloud and the radius of the drop to find e, found to be difficult

because of the evaporation

   i. On the other hand, he found a single drop could be balanced in the air by an electric field, eventually picking up an ion causing a movement in some direction
   ii. This resulted in the oil drop experiment, giving each charge and preserving it in midair, measuring the force on it, to confirm the electron charge

2. Absorbed radiation increases the kinetic energy of oscillating atoms, increasing the temperature, but resulting in increased radiation emission by electrons, reducing kinetic energy, called thermal radiation
   (a) At thermal equilibrium, the rate of absorption and emission are equal, such that higher freqencies are present at higher temperatures, due to higher energy
   (b) Ideal blackbodies emit and absorb all incident radiation by $R = P/A = \omega T^4$, where Stefan's constant (ω) is $5.67 * 10^8 W/m^2K^4$
      i. Non-blackbodies emit multiplied by some emissivity constant, based on factors such as color, temperature, and composition
   (c) Spectral distribution of the radiation of a blackbody also only depends on temperature, where the maximum emitted wavelength, $\lambda_{max}T = 2.898 * 10^{-3}m * K$, called Wien's displacement law
   (d) Blackbodies are approximated by a cavity with a small hole to let radiation in, found that the power radiated out, $R = \frac{1}{4}cu$, where U is the total radiation energy density in the cavity
      i. As a result, both are proportional to the wavelength, such that the energy density distribution can be found by the number of modes of oscillation
      ii. It is found that the number of modes of standing wave oscillation per unit volume, $n = 8\pi\lambda^{-4}$, and the Rayleigh-Jeans equation states that $u = kTn$, such that R can be calculated
      iii. As a result, while at higher wavelengths, it fits experimentally, at low wavelengths, it appears $R \to \infty$, called the ultraviolet catastrophy, such that total energy density over the spectrum from 0 to ∞ would be infinite as well
   (e) Planck's Law corrects for this, stating that since as λ approaches 0, n approaches infinity by classical formulas, u must be a function of wavelength, such that it approaches 0
      i. Classically, electrons oscillating produce waves with equal frequency, where the average energy is found by the energy distribution function, $n(E) = Ae^{-E/kT}$ based on the Maxwell-Boltzmann distribution function, such that average energy, $\bar{E} = \int_0^\infty Ef(E)dE = kT$
         A. In this equation, n is the fraction of oscillators with energy E
      ii. Planck found it agreed with expermental data if oscillator energy is a multiple of a discrete value, such that $E = nhf$, where h is Planck's constant
         A. The sum can be taken similarly such that $\bar{E} = \frac{hf}{e^{hf/kT}-1}$
         B. It follows that $u = \frac{8\pi hc\lambda^{-5}}{e^{hc/\lambda kT}-1}$, called Planck's Law, found to be a generalization of all known laws
   (f) Blackbody radiation has been used as proof of the Big Bang Theory, due to the universe predicted to act as a perfect black body in terms of energy distribution

3. In Hertz's spark gap experiment to generate EM waves and detect them, proving Maxwell's Theories, finding that light hitting a surface produced an electron current
   (a) Lenard later proved that it was electrons, and observed the current was proportional to the intensity (P = IA), but found that there was no minimum intensity needed as would

be classically expected, due to requiring enough energy to

   i. Fluxs of photons are the photons per second per unit area, related to intensity
   ii. Since the kinetic energy had to be great enough to avoid being pulled back to the metal surface cathode if there was a negative voltage, it required a voltage produced greater than $-V_0$, called the stopping potential
   iii. Thus, it was found that $KE_{max} = eV_0$, such that KE_{max} was independent of the light intensity as well, rather than increasing the electron kinetic energy

(b) Einstein postulated as a result that Planck's quantization was universal, such that E = hf for all light quanta, such that $eV_0 = hf - \phi$, where ϕ is the work function, characteristic of the metal, to remove an electron
   i. This is equal to the maximum kinetic energy by energy conservation, though some electrons lose energy when leaving the metal further
   ii. As a result, the threshold wavelength is equal to the work function divided by h
   iii. This also explains the lack of a time lag for the production of photoelectrons, instead of the calculated time for enough energy if it is spread evenly over the surface, as assumed classically

4. Xrays originally were discovered by Roentgen with a cathode ray tube, noticing rays from the collision of electrons and the glass tube could activate flurescent photographic film and pass through opaque materials
   (a) He later observed no material was opaque, though less rays could pass through with higher densities
   (b) He stated that their apparent lack of magnetic deflection, refraction, or interference, was due to a very short wavelength, finding they were defracted by a crystal lattice, also proving a regular crystal array
   (c) He found they were produced by eletrons when deflected then stopped by the atoms of a target
   (d) He then thought to use Bragg places, or face-centered cubic molecular structures of NaCl crystals, analyzing the scattered waves from each atom to view xray diffraction
      i. The waves are in phase regardless of wavelength if the scattering angle is equal to the incident angle for two waves hitting atoms in a plane
      ii. This condition is called the Bragg condition, true if $2dsin(\theta) = m\lambda$, where d is the distance between atoms
      iii. The amount of ionization from xrays can then be measured to get the intensity of each wavelength, after it has been corrected by the Bragg condition to get the correct angle
   (e) This produces a spectra for the xrays produced, based on the anode of the material, able to be used to determine the atomic spacing
      i. This produces both the characteristic spectrum of sharp lines and the continuous spectrum, the former which is specific to the material
         A. Maxwell had previously predicted the continuous spectrum was due to the electron bombardment/deacceleration in the strong electric field, though the cause of the characteristic was unknown
      ii. There is also a cutoff wavelength, independent of the material, based on the energy of the bombarding electrons, by $\lambda = \frac{1.24*10^3 nm}{V}$, called the Duane-Hunt Rule
         A. This is explained as the opposite of the photoelectric effect, such that all the kinetic energy is converted ($\lambda = \frac{hc}{eV}$)

5. Compton later measured the scattering of xrays by free electrons, proving further both the photon and special relativity
   (a) He observed that the scattered xrays were more easily absorbed, considering that the collision allowed an electron to absorb some of the photon energy, such that the wavelength became longer
   (b) As a result, he derived the Compton equation mechanically, stating $\Delta\lambda = \frac{h}{mc}(1-cos(\theta))$, where $\frac{h}{mc}$ is called the Compton wavelength of the electron
      i. This was observed for xrays due to the percent change in wavelength only being noticable for very short original wavelengths