PHY 571: Quantum Physics

John Venables

5-1675, john.venables@asu.edu

Spring 2008

Introduction and Background Topics

Module 1, Lectures 1-3

Introduction to Quantum Physics

- Discussion of Aims
- Starting and End Points
- Optional Diagnostic Test
- Effort and Improvement over Course
- Assessments: 5 problem sets and 2 unseen exams: Mid-Term + Final
- Web pages, start from: http://venables.asu.edu/quant/index.html

Structure of the web pages & modules

- Start with first half semester timetable at http://venables.asu.edu/quant/timetab1.html
- The modules are outlined and cross-linked at http://venables.asu.edu/quant/quantmod0.html Use other resources from this page, starting with Course books and web-supplements
- The course has a 5-modules, more or less corresponding with 5 problem sets. We start at http://venables.asu.edu/quant/quantmod1.html

Module 1: Background Information

Topic 1: Black-body Radiation

- ½kT per mode... equipartition of energy theorem
- *e.g.* $\frac{1}{2}mv^2 = \frac{1}{2}m(v_x^2 + v_y^2 + v_z^2) = 1.5kT$; explore relationship with the *Kinetic Theory of gases*
- Apply to modes of a cavity: each vibrating mode has kT (1 potential energy, 1 kinetic energy "term")
- Raleigh-Jeans law: $u(\nu,T) = (8\pi\nu^2/c^3)kT$, *Ultraviolet Catastrophe*
- Planck formula: $u(\nu,T) = (8\pi\nu^2/c^3)kT[\text{factor}]$, and $[\text{factor}] = x/(e^x-1)$, with $x = (h\nu/kT)$,

  Bose-Einstein distribution

Outline and references

Consequences of the Planck Distribution

- *Removes* UV catastrophe, and
- *Introduces* Energy Quanta, $E = h\nu = \hbar\omega$, and agrees with the Thermodynamic result that the

  Energy/unit vol, U = integral $[u(\nu)d\nu] = aT^4$, with the constant $a = 7.5662 * 10^{-16}$ $J/(m^3K^4)$
- Formulae (G3,p3; G2,p5) as $a = (\pi^2k^4/15\hbar^3 c^3)$
- Emissive power/unit area, E $= \sigma T^4 = (c/4)T^4$, Stefan-Boltzmann law, with the constant

  $\sigma = 5.67051(19) * 10^{-16}$ $W/(m^2K^4)$

Planck's law: experimental evidence

- Cosmic microwave background: radiation at $T = 2.735 \pm 0.00?$ K, left over from big bang (*find an astronomer for details*)
- Specific heat of materials, Dulong-Petit $C_V = 3Nk$ at high T, at low T << this value:
- ~ $\exp(-h\nu/kT)$, Einstein model, freezing out modes
- ~T^3, Debye model, phonons, long wavelength modes
- Project for this class shows Planck distribution http://venables.asu.edu/quant/DavidS/index.html

"Quick" Problems: Black body Radiation

1) Check units of *E*, the emissive power/ unit area;

2) a) What are the units of Planck's constant, *h* ?

b) Boltzmann's constant, *k* ?

3) In the expression for U, find the value of the constant "a" in the c.g.s. system (1 erg = 10^{-7} Joules (J), 1 cm = 10^{-2} m).

Longer problem (see problem set #1)

Explore the relationships between *black body radiation* and the *kinetic theory of gases*

Topic 2: Photoelectric Effect

- Electro-magnetic radiation, frequency ν, wavelength λ, has $\lambda\nu = c$, velocity of light *Wave behavior* and *Electromagnetic Theory* (Maxwell, 1865 onwards)
- Shine light onto a surface in good vacuum, electrons are emitted. Energy of emitted electron governed by frequency, *not* by the *intensity* of the light
- $\frac{1}{2}mv^2 = h\nu - W$, with $W = eV$ = work function of the surface (Einstein 1905) *Particle behavior* and *Energy quanta (photons); intensity* = *#photons*
- Photoemission is the modern version of the P.E., used to study electronic properties of surfaces and electronic energy bands in materials generally

Topic 3: Compton Effect

- Inelastic scattering of X-rays, high energy photons with energy E and momentum $\boldsymbol{p}$ (vector quantity)
- $E = h\nu = \hbar\omega$ and $\boldsymbol{p} = \hbar\boldsymbol{k}$ ($\boldsymbol{k}$ = wavevector, $k = 2\pi/\lambda$),
- Magnitude of $p = \hbar\omega/c = h/\lambda$ (de Broglie, 1923)
- Photon loses energy in a (2D) relativistic collision, such that $\lambda' > \lambda$, the shift is governed by Compton wavelength, $\lambda_C = h/mc = 2.42631058(22) * 10^{-12}$ m
- In a 2D collision, $\lambda' - \lambda = \lambda_C (1 - \cos(\theta))$, where θ is the scattering angle. To derive this we need
- $\boldsymbol{p} = \boldsymbol{p'} + \boldsymbol{P}$, $E = [(m_0c^2)^2 + (pc)^2]^{0.5}$ *i.e.* relativistic kinematics. See student project and comps questions

Topic 4: Particle Diffraction

- Based on de Broglie relation, $\lambda = h/p$ for particles: *both particles and waves can diffract...*
- electrons, neutrons, atoms, ...buckyballs (C_{60})...??
- Two experiments in 1927 demonstrated diffraction with electrons: Davisson & Germer, and Thomson
- "Slow" electrons (D&G) diffracted off Nickel crystal surface. Modern techniques: LEED, LEEM, SPLEEM
- "Swift" electrons (G.P. Thomson, son of J.J., the "inventor" of the electron in 1897), diffracted through thin films. Modern techniques: TEM, TED, HREM
- *slow, swift, low or high energy are all relative terms*

Topic 5: The Bohr Atom

- Nucleus, concentrates almost all the mass in very small region (α-particle scattering, Rutherford, 1911)
- Electrons, in "planetary motion" around the nucleus. *All the problems with the Bohr model arise from the inadequate visualization of what "planetary" means*
- Historically important (1913), but mainly as a dead-end. The next level of development beyond Hydrogen atom (Somerfeld, 1920's elliptical orbits) didn't work
- Circular orbits + quantization of angular momentum: $\boldsymbol{L} = \boldsymbol{r} \times \boldsymbol{p}$ (L = mvr = n$\hbar$); equivalent to the orbit circumference $2\pi r = n\lambda$. See student project + notes

Big success for the Bohr atom, *but...*

- Explained the Rydberg formula quantitatively for H: $1/\lambda$ = const. $[1/n_1^2 - 1/n_2^2]$, and the constant (R) was correct, as deduced from existing spectroscopy results
- $R = (Z^2 e^4 m/4\pi c\hbar^3)$, the Rydberg constant, $Z = 1$ for H
- Postulated the stability of orbits, *but didn't really explain them*: $mvr = n\hbar$ is an *ad-hoc* assumption
- Circular orbits are *directional objects*, but an atom is spherically symmetric in its ground state; so atoms are not "planetary systems", but "fuzzy balls"; n, l, m quantum numbers. "Bohr-like orbits" for high l-states
- Animations of orbitals: see Web-based Resources