Chapter 4

- Last time we discovered that sometimes we must treat light as a wave and sometimes we need to treat it as a particle. This is not very satisfactory after all physicists attempt to define models which are good over a wide range of circumstances (i.e. we like that Newton's Gravity works for a falling ball on earth and can also explain the orbit of Jupiter around the sun.)
- Today we want to confront another problem with our view of the universe. That is the behavior of subatomic "*particles*" (I am showing some bias)
  - Protons, electrons, and neutrons
- These objects behave very much like particles, we can collide them into one-another and at least at low energy they act like billiard balls hitting one another. The leave definite "tracks" in particle detectors.

de Broglie Hypothesis

- In the early 1900's there was plenty of evidence that small atomic and subatomic "objects" were like hard particles. Just as there had been plenty of evidence that light was a wave and physicists were surprised by the particle nature of light in the photoelectric effect, physicists were about to be surprised by the **wave nature of small particles**.

- In 1923 (about the time Compton was showing more evidence that light could act like a particle), Louise de Broglie proposed that a beam of particles (e^-, protons) would display wave-like behavior (i.e. a diffraction or interference pattern). Recall from Relativity

$$\frac{pc}{E} = \frac{v}{c}$$

For a photon v = c we have

$$\frac{pc}{E} = \frac{c}{c} \;\Rightarrow\; pc = E \;\Rightarrow\; pc = \frac{hc}{\lambda}$$

$$\Rightarrow p = \frac{h}{\lambda} \quad \text{or} \quad \lambda = \frac{h}{p}$$

Wave Nature of Particles

- de Broglie’s insight was that since special relativity showed no real distinction between matter and energy and thus no real difference between photons (light) and other particles. So he claimed this equation should be good for all particles. The “λ’ in the expression above is how known as the “de Broglie” wavelength.
- Example (Q4x.1)
  - Electron v=0.01c p = mv (approx.)

- Visible light is several hundred nm

Matter Waves

- This small wavelength makes it technically difficult to observe the wave properties. Recall for interference:
  - (1) Slit width ~ λ (so we need *small* slits or something equivalent)
  - (2) Distance between peaks in interference pattern (small angle approximation.)

$$s \approx \frac{\lambda}{d} D = \frac{h}{dp} D$$

- Also note for $\lambda = h/p$ when beam p *increases*, λ *decreases* which makes it tougher. We will see a specific example in a moment.
- If we were to try to design an experiment to look for an interference pattern of particles we need a "monochromatic" beam of particles.
  - What does this mean?
    - Light:
    - Particle:

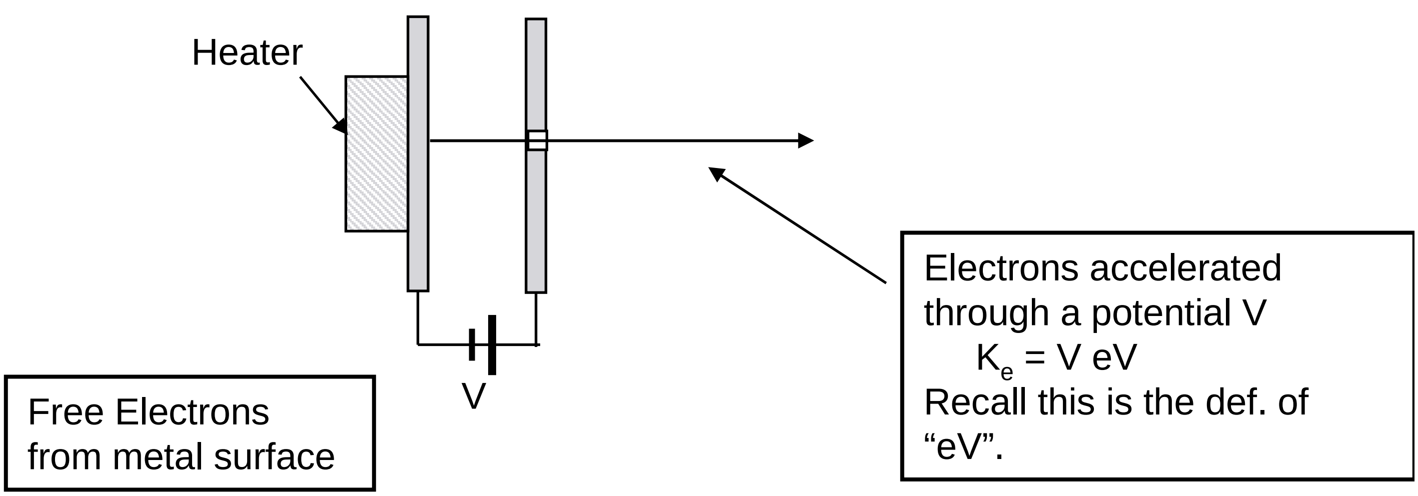
Matter Waves

- So we can express the de Broglie wavelength in terms of K (Note: this is an approximation for the nonrelativistic limit and for m>0)

$$\lambda = \frac{h}{\sqrt{2mK}} = \frac{hc}{\sqrt{2Kmc^2}}$$

- How can we make a monoenergetic beam of particles? There are several, but let’s consider a technique for electrons since this was accessible in the early 1900’s.

Simplified “Electron Gun”

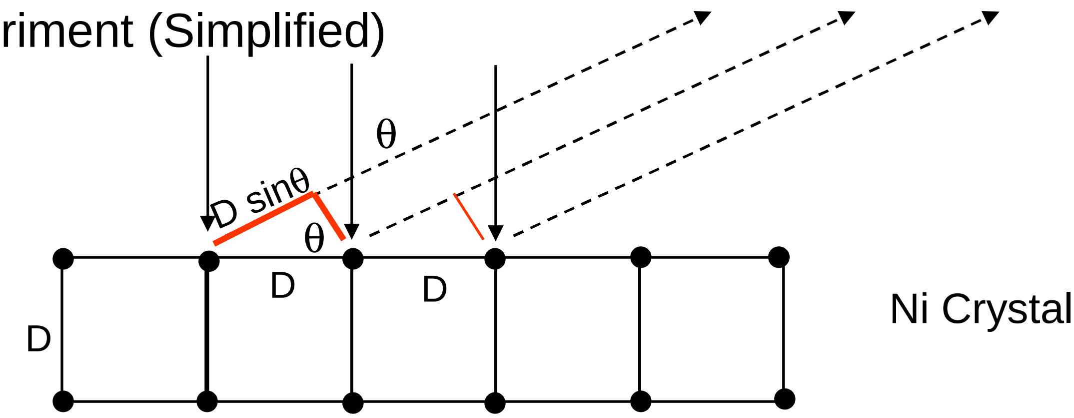


$$\lambda = \frac{hc}{\sqrt{2V(5\times10^5\,\text{eV})}} = \frac{1240\,\text{eV}\cdot\text{nm}}{\sqrt{10^6 V\,\text{eV}^2}} = \frac{1.240}{\sqrt{V}}\,\text{nm}$$

If V=100 Volts λ_e = 0.124 nm

Matter Waves

- Now we have a source of (nearly) monoenergetic particles making two slits that are small enough and closely spaced is more problematic. (The ability to make such slits would not come until the 1960's) Nonetheless, in 1925 two physicists (Davisson and Germer) observed interference of electrons. (Read introduction of Section 4.4 for how they stumbled onto this result.)
- Experiment (Simplified)



- (A) Rays 1,2,3 all differ by multiples of Dsinθ where D is the interatom spacing. Condition for *Constructive Interference:* $n\lambda = D\sin\theta$

$$\theta = \sin^{-1}\frac{n\lambda}{D}$$

- (B) Davisson-Germer used an electron gun with a voltage of 54 eV.

$$\lambda = \frac{1.240}{\sqrt{V}}\,\text{nm} = 0.167\,\text{nm}$$

Matter Waves

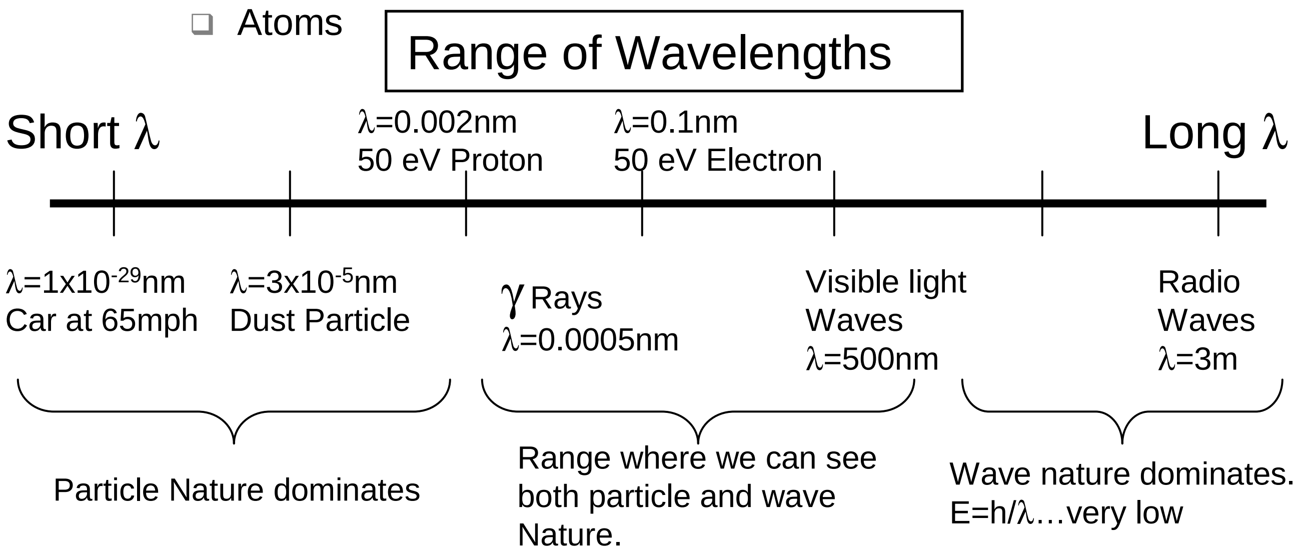
- (C) Let’s find the first angle with constructive interference (n=1)

- This is the angle where Davisson and Germer observed a “bright spot” which is the electron. Note that the second interference angle (n=2) is sin $\theta > 1$, so not real.
- (D) The second (and even 3rd and 4th) layers of atoms. We will have scattering off these layers as well which makes the problem much more complicated.
- When Davisson & Germer first observed the bright spot (note there is only a single constructive interference anlge…not your typical interference pattern.) They were not sure what was going on. They had not heard of de Broglie’s hypothesis. But they were made aware of the idea. After a series of experiments they were convinced they were observing wave-like interference of “particle” beams.

  - ***<u>“Partilces” behave like waves!!</u>***

Matter Waves

- Many other interference experiments have been conducted over the years.
  - 1960's Actual two-slit interference with electrons
    - See Pattern Page 69 of text
    - American Journal of Physics, 42:5, 1974)
  - Similar experiments with
    - Neutrons
    - Protons
    - Atoms



- See examples Q4.4 & Q4.5 to see how impractical it is to conduct interference experiments with some of these particles.
- Phenomena that we thought of as waves (light) can act like particles
  - Photoelectric Effect
- Phenomena that we have thought of as particles (electrons) can act like wave
  - Interference Patterns
- No physical model that you have studied in 13x can fully explain all these phenomena…we need a new model! ***<u>QUANTUM MECHANICS!</u>***