PHYSICS 102N
Spring 2022

Week 11

Light emission and absorption, Quanta and Matter Waves

Accelerated charges emit electromagnetic waves *)

- Examples:
  - Radio antenna: Alternating voltage drives electrons back and forth 94.9 million times/second
  - Bremsstrahlung: Electrons slamming into solid anode give off x-rays (-> dentist)
  - Synchrotron radiation: Electrons going in circles give off IR - visible - UV - soft Xray radiation
    - Enhance through “wigglers” and “undulators” - FEL
  - Hot plasma (surface of sun, welding arc)
- What about ordinary atoms and molecules?
  - not as easy to understand…

*) Brain Teaser: Do electromagnetic waves accelerate charges?

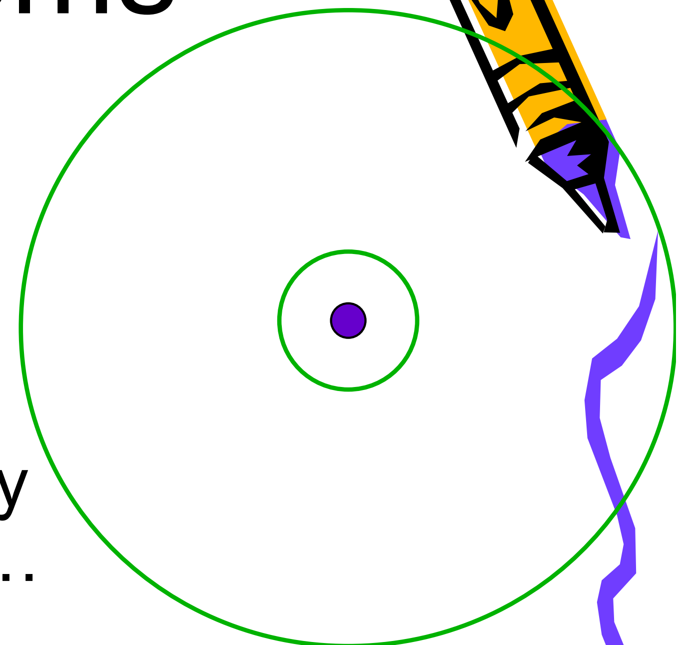
Electrons in Atoms

$$\vec{\mathbf{F}} = q\vec{\mathbf{E}} \Rightarrow \quad \vec{\mathbf{a}} = \frac{q}{m}\vec{\mathbf{E}}$$

- +: They **are** accelerated, zipping around on "orbitals" => changing direction constantly ("mini-synchrotrons"?)
- -: But they can't possibly **keep** giving off electromagnetic radiation <=> violation of energy conservation! (or crash into nucleus)
- Postulate (Bohr, Sommerfeld) There are certain orbits which are stable and do not radiate; they have fixed ("quantized") energy levels

  only transitions between these orbits can give rise to EM radiation like light, carrying away the energy difference

Energy levels in Atoms



- Example: Hydrogen
  - Energy levels: -13.6 eV, -3.4 eV, -1.5 eV, -0.85 eV …
  - Possible transitions can carry away 10.2 eV, 12.1 eV, 1.9 eV, 2.55 eV,…
- Surprise! Energy given off as electromagnetic radiation determines frequency of wave: $\Delta E = hf$
  - Max Planck's constant *h*: one of only a handful truly fundamental constants in nature

$h = 6.63 \cdot 10^{-34}$ Js => $1/h = 1.51 \cdot 10^{33}$ Hz/J = $2.4 \cdot 10^{14}$Hz/eV
=> 2 eV corresponds to 620 nm (orange); $\lambda = c/(h^* \Delta E)$

Spectra

- Every species of atoms (element) or molecules (compound) has its very specific set of energy levels and therefore possible light frequencies => distinctive pattern of emission lines
  - analyze with spectrograph, e.g. diffraction grating
  - "element fingerprint" - can identify elements from crime lab all the way to the edge of the universe
  - characteristic colors from discharge and evaporation lamps (sodium street lights, "neon" signs); coloration of flames, plasmas (e.g., aurora borealis/australis)
- Endless sequence of excitation (discharge = electron bumping, or heat = atom bumping) and emission (light, UV, IR radiation)
  - Energy transferred from electrical or internal (heat) to light
- Reverse: Absorption (Light energy gets "soaked up" to excite atom to higher energy level)
  - Absorption lines in star light indicates cooler gas in between (discovery of Helium!)

…more complicated

- Fluorescence:
  - Absorb higher energy photon (UV) => jump several levels => de-excite level by level => re-emit light of lower frequency (visible)
    - t-shirts, crayons, minerals and fluorescent lights
    - scintillator material for nuclear and high-energy physics
- Phosphorescence:
  - Atoms/compounds with long-lived (“metastable”) excited state - de-excite only after a while - long afterglow (CRT phosphor, glow-in-the-dark toys)
- Stimulated Emission:
  - Longer-lived state de-excites “in sync” when exactly the right frequency light passes by (photon doubler)
  - **L**ight **A**mplification by **S**timulated **E**mission

Incandescence

- Solids, very dense fluids, plasmas:
  - neighboring atoms/molecules interact *), bump into each other, oscillate (Doppler effect)
  - Lots of individual lines (complicated electron orbit structure); lines are broadened, “washed out” or totally overlapping
  - Extreme: Metals
    - some electrons are “shared” among many atoms
    - see a very fine-structured spectrum of energy levels (quasi-continuous)
- => Continuous Spectrum of light at all wave lengths
  - Remember Thermal Radiation! $f_{max} \propto T$…

*) Compare to coupled pendula: Resonance frequencies shift, damping broadens width of resonances

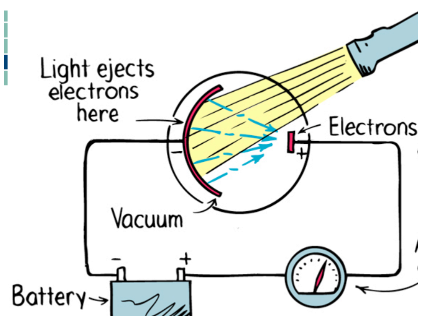
Light "particles": Photons

- Light ***travels*** as a continuous, smooth wave spread out over some volume of space
  - typical wave behavior: interference, diffraction, polarization,…
- BUT: Light gets ***emitted*** and ***absorbed*** only in finite packages of Energy $E = hf$, by only one atom (electron) at a time
  - typical particle behavior: indivisible (no energy exchange of $hf/2$ possible), localized (only at one spot, not everywhere at once)
- Resolution: Particle-Wave duality

Somewhat simpleminded version:
Light propagates like a wave and interacts like a particle
Wave intensity tells us the probability for the particle (photon) to "materialize right here"

Examples for Photon Picture

- Light sources
  - Light beam made of photons emitted by one atom at a time de-exciting (photon energy $E = hf$ = energy change in atom)
- Imaging
  - Photographic film: Image builds up one AgCl molecule at a time
  - Modern image sensors (CCDs): Image builds up one pixel at a time (brightness: photon counting)
- Photo-electric effect (Einstein's Nobel Prize)
  - Shine light of various frequencies onto metal surface, look for emitted electrons and measure their energy



      - Below cut-off frequency, NO electrons emitted regardless of how intense the light
        - Require minimum energy $E_{min} = hf_{min}$ to remove electron from metal
      - Above cut-off, electron energy increases with light frequency (regardless of intensity)
        - $E_{el} = hf - E_{min}$
      - Intensity only determines how many electrons are emitted per time

Which of the following is an accelerated motion that does **not** lead to emission of electromagnetic radiation?

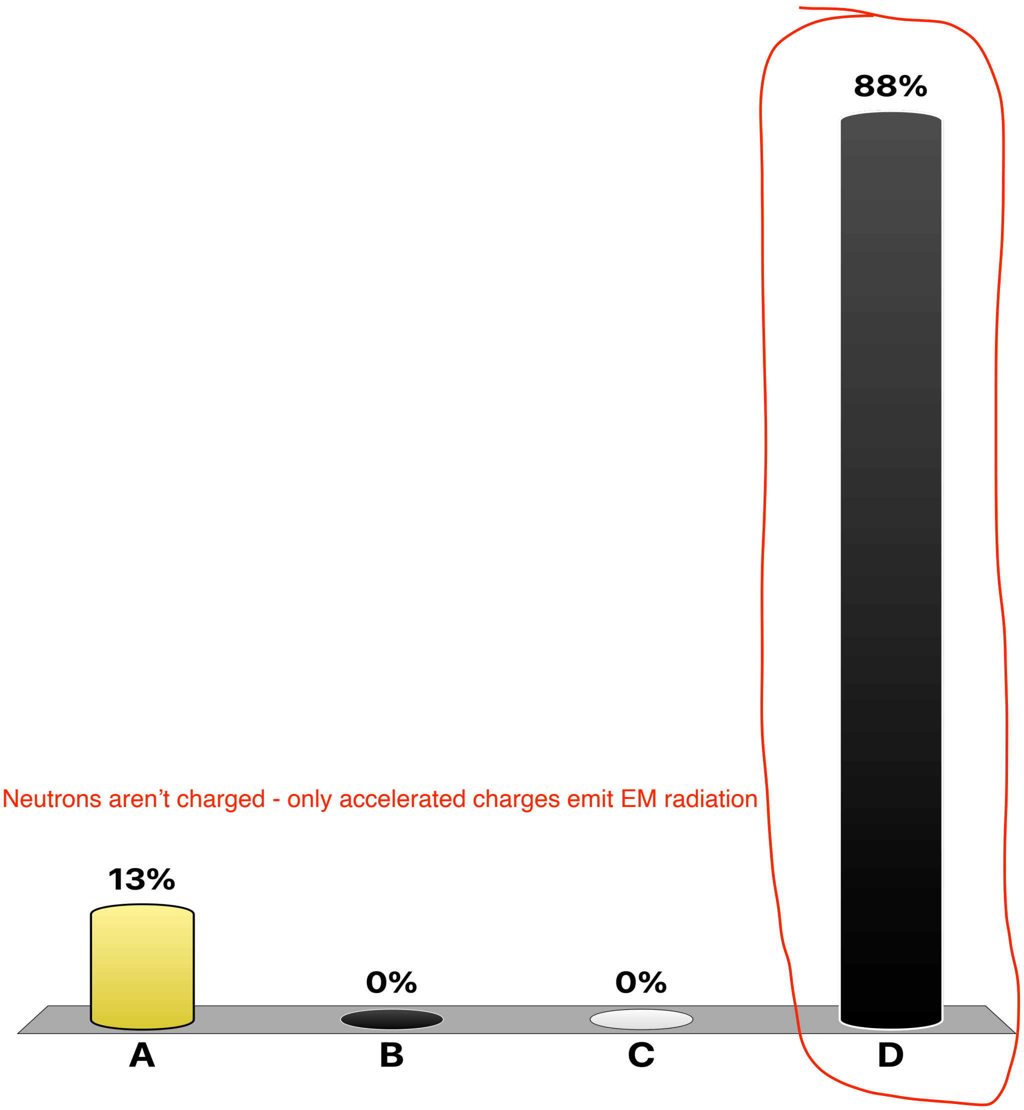
A. An electron following a curved path in a magnetic field

B. An electron slamming into a piece of tungsten

C. Electrons in an antenna sloshing back and forth

D. A neutron being slowed down by water

Neutrons aren't charged - only accelerated charges emit EM radiation



Which of the following processes is **not** possible on a **single** cold atom?

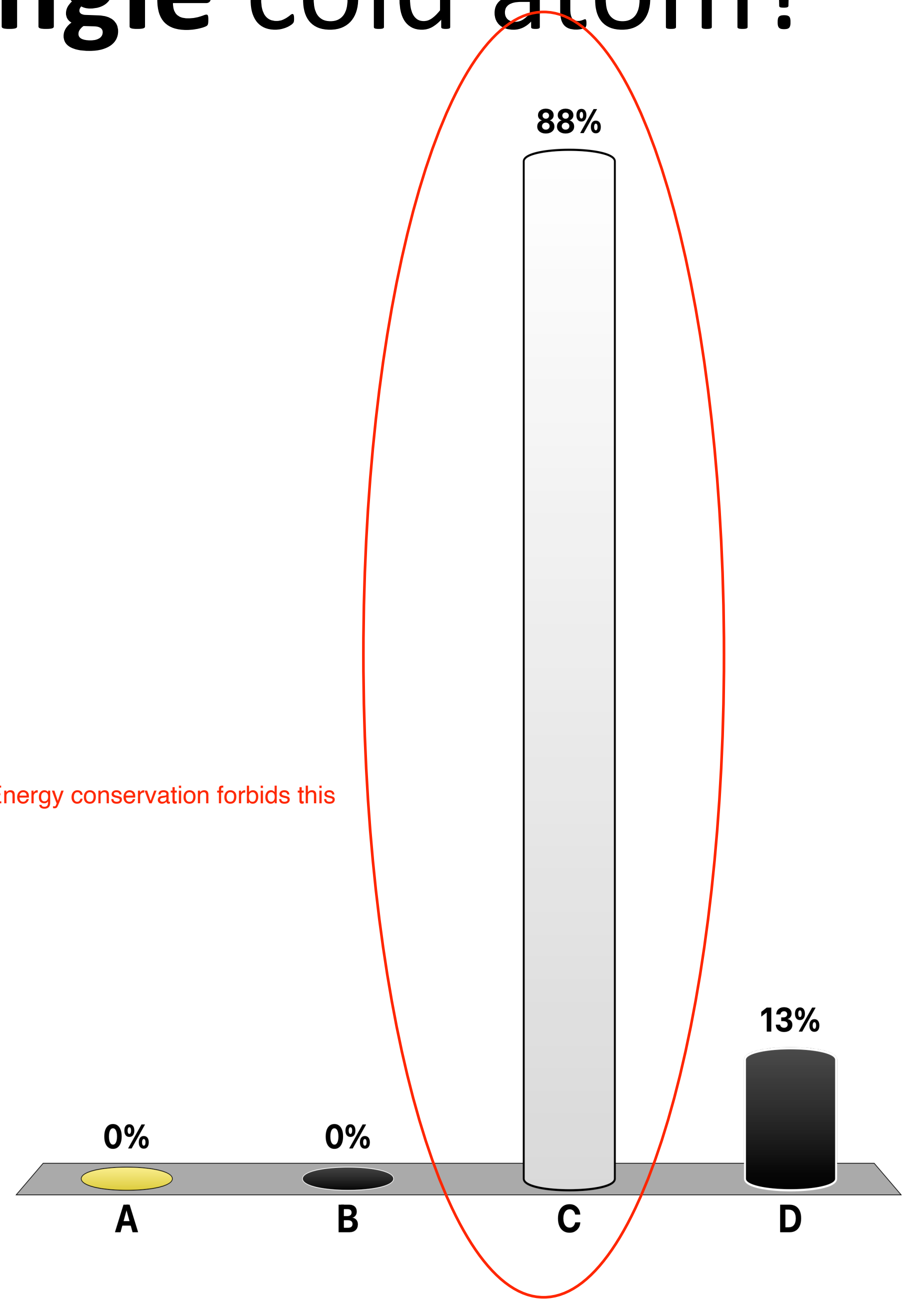
A. The atom absorbs a photon of red light and then emits a photon of red light

B. The atom absorbs a photon of ultraviolet light and then emits two photons (one green, one infrared)

C. The atom absorbs a photon of red light and then emits a photon of green light

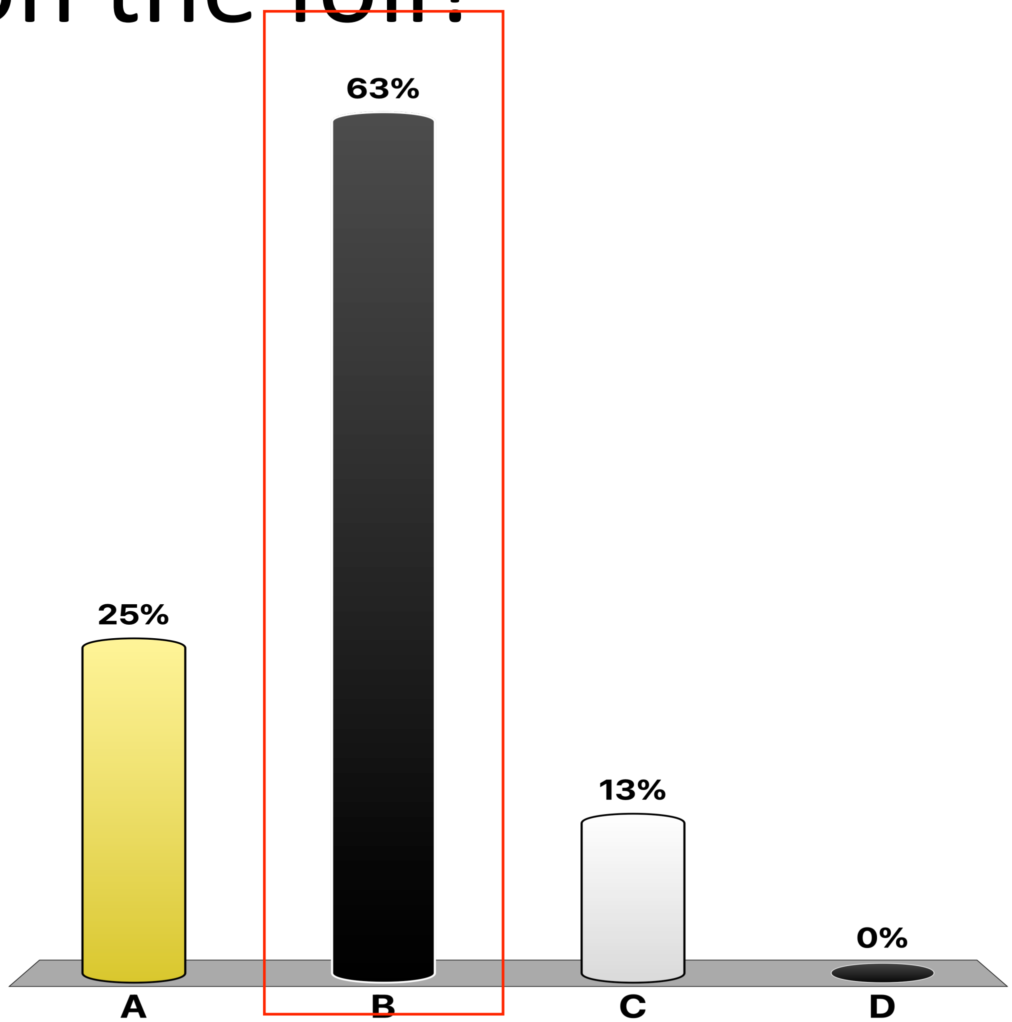
D. The atom gets excited by an electric discharge and then emits a photon of blue light

Energy conservation forbids this



A blue laser is illuminating a foil, which emits 1 eV electrons whenever the laser is turned on. What happens if we shine TWO identical blue lasers on the foil?

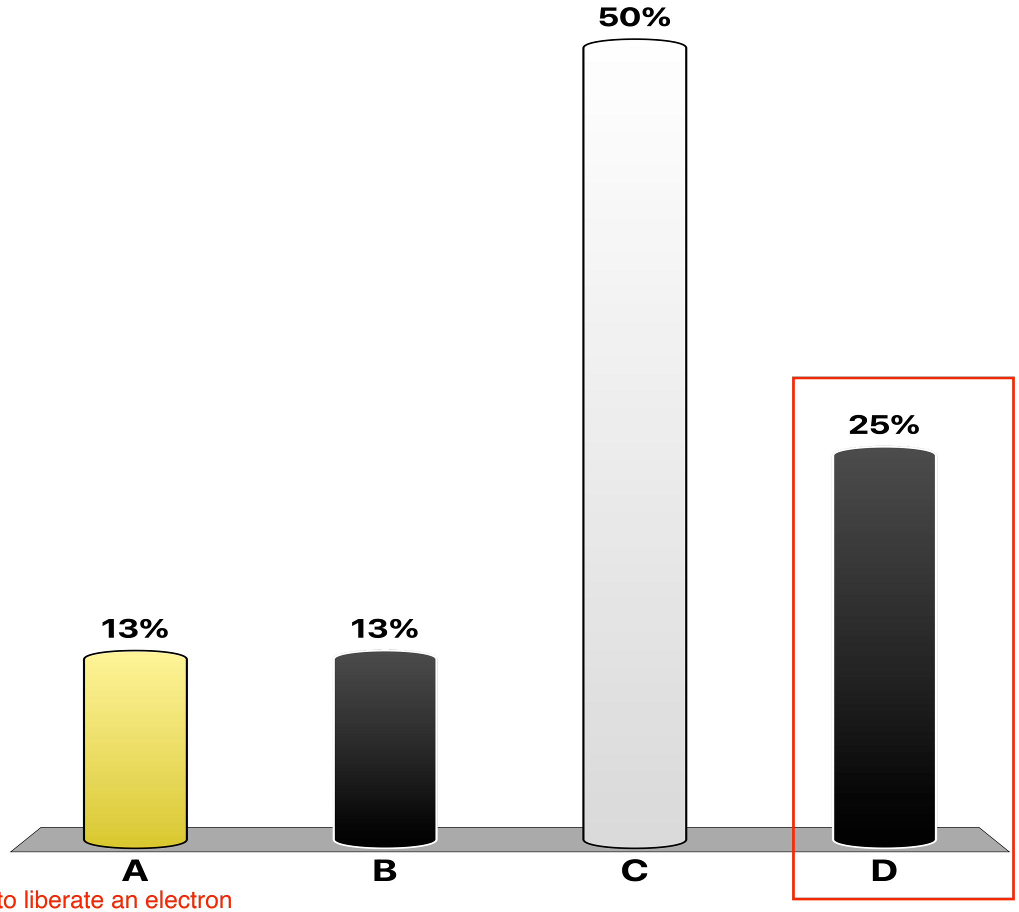
A. The electrons emerge with more energy (2 eV)
B. Electrons emerge with the same energy, just double as many.
C. The effect is the same as a single laser.
D. No electrons are emitted.



A blue laser is illuminating a foil, which emits 1 eV electrons whenever the laser is turned on. What happens if we shine TWO **RED** lasers on the foil?

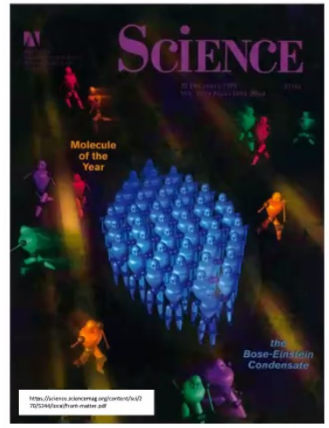
(*Note*: a blue photon has 3 eV energy, and a red one 1.7 eV)

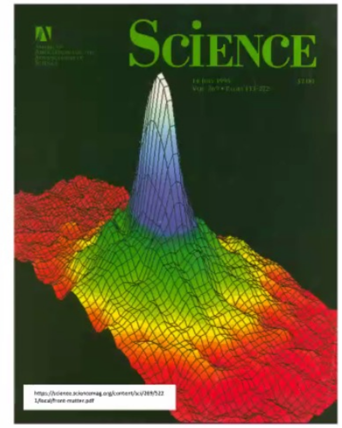
A. The electrons emerge with less energy
B. Electrons emerge with the same energy, just fewer.
C. The effect is the same as a single blue laser.
D. No electrons are emitted.



No single laser photon has enough energy to liberate an electron

“Matter” Waves!





- Duality applies to all objects in nature
  - Electrons also propagate as waves (and interact as particles)
    - double slit interference
    - diffraction
    - imaging (electron microscope)
  - Also applies to quarks, nucleons, nuclei, whole atoms (BEC), mosquitoes, bowling balls, planets…
  - de-Broglie picture: wavelength = *h*/momentum
    - Example: Electron going at 1/1000 of speed of light:

$$\lambda = \frac{6.6 \cdot 10^{-34}\,Js}{9.11 \cdot 10^{-31}\,kg \times 300{,}000\,m/s} = 2.42 \cdot 10^{-9}\,m$$

    - not observable in everyday life because λ becomes tiny and interference/diffraction effects are proportional to λ/s

Heisenberg's Uncertainty Principle

- You can never determine position and momentum (in the same direction) with infinite precision simultaneously ($\Delta p_x \Delta x \geq h/4\pi$)
- Explanation
  - Use single slit to limit Δx
  - Diffraction will distribute outgoing wave over angular range of order $\lambda/\Delta x$
  - This leads to uncertainty on sideways (x-) momentum $\Delta p_x = p \cdot \lambda/\Delta x$
  - But $p = h/\lambda$ => $\Delta p_x = h/\Delta x$
  - Exact expression comes from proper definition of "uncertainty"
- True for all particle trajectories (including photon trajectories = light waves)
  - The more you pin something down, the less you know about where it will go next…

=> Quantum Mechanics

"NATURE IS WEIRD"

1. All objects can be represented by waves describing their propagation through space
2. The wave length is $\lambda = h/p$ and frequency is $f = E/h$
3. Simultaneous measurement of position and momentum is limited by Heisenberg's uncertainty principle
4. Stable orbits = standing waves (see later)
5. If you build an apparatus that registers a localized interaction (atom excitation, electron emission, pixel activitation…), you can only predict probability for particle to be at a given point:
   $P(\mathbf{r})$ = Wave Intensity($\mathbf{r}$) (Amplitude squared)
6. Interaction is "all or nothing" (quantized)