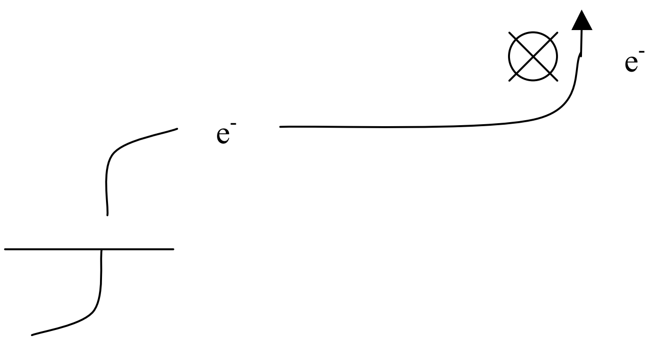
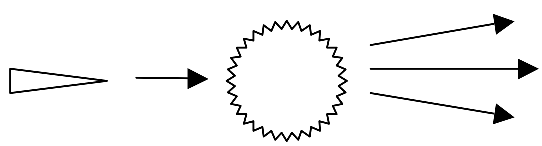
Atomic Structure L12p1

- Cathode rays (JJ Thompson and the electron)

- by placing a conducting metal plate near an electrical force one can remove electrical 'current' from the plate. But what is this current made of? One can then pass the current thru a magnetic field (shown as circle with X in it below). If the current is made of a single type of particle, the current will bend according to the charge and mass of the particles within it. This was observed, and the electron was discovered.



- Measure properties of electron (charge/mass)
  - Assume atom is blob of positive "pudding" with electrons embedded
  - Or fragments of onion in a meatball!
    - Onion weighs almost nothing, meatball has no heavy components (uniform mass distribution in meatball).
    - So when shoot bullet at a meatball, it largely passes thru without altering it's motion (momentum)



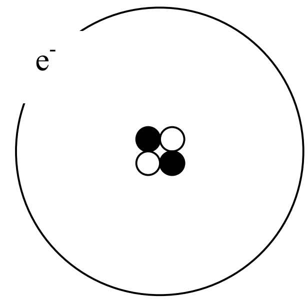
Expected result

Scattering experiment (Rutherford)

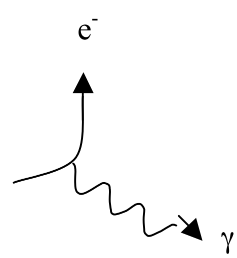
α particles directed at a thin gold foil

Gold has a large mass per atom: (ie, the non onion part of meatball is massive)

- Expect same behavior
- Except sometimes, α comes back at you!
  (bullet reflected back by meatball)
  ("cannon ball stopped by a tissue")
- So positive charged mass of atom must be concentrated at center of an atom
  - This gives us a "Planetary model of atom"



- Problem
  - When electrons in orbit around positive nucleus, they are accelerated to bend around the nucleus. Accelerated charges emit energy in the form of photons:
  -

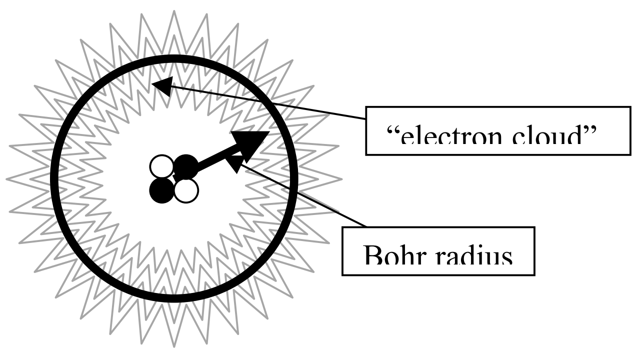


- So e^-'s loose energy and spiral into atomic nucleus
  - atomic structure not stable
  - but we see stable atoms

Quantum Model of the Atom, L12p4

Use a probabilistic description (ie Schrödinger's functions)
- Electrons can be "spread out" around nucleus

- consider atom to be like 'particle in a box'
  - electrical attraction of positively charged nucleus binds electrons to vicinity of atom
  - the atom has a characteristic size, call it the radius, R within which the electrons are bound
    - the region the electrons are confined to is called the electron 'shell'. This is a probabilistic region where electrons are most likely to be.
  - this size dictates the energy levels that the electrons are allowed to take (i.e. it indicates which wavelengths the electrons may have to fit within the box of the atom.)
    - the energy level is denoted by the 'quantum number', n
    - the energy level is related to the radius of the electron shell
  - electrons in stable shells do not emit radiation
    - they are not 'orbitting' around the nucleus, so they are not accelerated in the classical sense of the 'planetary model' of the atom.



Radiation is emitted when an electron makes a transition from one level to another ($\Delta\lambda$)

- $E_i - E_f = h\,f$ where f is frequency of γ emitted.
- Gives overall correct description of spectral lines for elements

Particle Spin

At a very detailed level, the atomic spectra had 'fine structure' that was not understood from the initial quantum mechanical models. When electrons are moving very fast, it turns out quantum mechanics expects a property of particles to matter. Any fundamental particle, like an electron, can have a rotational status we call 'spin'. This is hard to imagine if we consider the classical point particle idea of an electron to be spinning. But an electron is not a point particle, and so does exhibit a spin, sort of like a top.

In the environment of an atom, the alignment of the spin axis does matter. Slightly different energy levels for the electron are present based on if the spin of the electron is 'up' or 'down'.

It was also observed that electron shells 'filled up' such that only certain well-defined numbers of electrons occurred in each shell. Another way to say this is that it was observed that not all electrons went to the lowest energy, or 'ground' state. This gives us the Exclusion Principle

Exclusion Principle L12p5

"No two electrons can ever be in the same quantum state; therefore, no two electrons in the same atom can have the same set of quantum #'s"

- If have multiple electrons
  - Fill up successively higher energy levels
    - If there is a lower, unfilled level,
      - atom will radiate photons (i.e. energy) until it's filled
    - Fill sub-shells then graduate to next shell
- Chemical Elements
  - Defined by number of electrons
  - Those in periodic table in columns
    - Have the same # of electrons in outermost shell
    - And have similar chemical properties

Nuclear Structure L13p2

- From Rutherford □ nucleus $r \approx 10^{-14}$ m
  (for atom $\approx 10^{-9} - 10^{-10}$ m)

- 1931, discovery of the neutron. The neutron is similar to the proton, but has zero electrical charge and a slightly larger mass. ($M_p \approx M_n \approx 2000\ M_e$)

- Composed of protons and neutrons
  - These are generically called 'nucleons' since they are so similar
  - Each element has unique # of protons
    "isotopes" for each element have different #s of neutrons
    Mass is expressed as rest energy equivalent
    For proton: $E_R\ M_pc^2 = 930$ MeV
    $1\text{eV} = 1.6 \times 10^{-19}$ J
  - the fraction of neutrons goes up for heavy nuclei

- Protons positively charged, so they repel each other
  - Something must hold them together in the nucleus
    "strong nuclear force"
  - Very short range □ nuclei don't get bigger past $A \approx 10^2$
  - Does not affect electrons

- Measurements Indicate that strength of strong force (i.e. its 'binding energy') increases, per nucleon, until reach 60 nucleons
  - then size of nucleus oversteps limit of strong force reach
  - nucleons on opposite sides of nucleus cannot feel each other's strong attraction

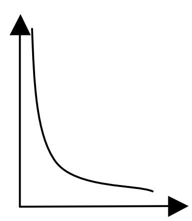
Radioactivity L13,p3

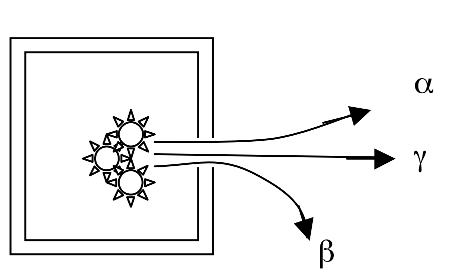
- Observed (Becquerel 1896)
  - Uranyl potassium phosphate crystals (uranium chemical compound)
    - A kind of Invisible emission or radiation
    - Unstimulated
    - Darkens photographic plates, even when covered to block visible light
- Curie's discovery of new elements (Po & Ra)
  - Some substances more so than others
-
- Experiment supports idea of
  - Disintegration or "decay" of unstable nuclei
  - Different penetrating power, mass, and charge of three kinds of radiation:

Penetrate paper	α decay	He nucleus emitted
mm Al	β decay	$e^{\pm}$ emitted.
cm Pb	γ decay	high energy photon emitted

Decay of atomic nuclei is Probabilistic in nature

- Start with sample of N_0 atoms
- # undecayed declines exponentially with time
- Half-life → time interval during which half of a given number of radioactive nuclei decay.





α decay: L13p4

- Nucleus of He emitted in radioactivity from heavy nucleus
  - Potential barrier much higher than energy of α within nucleus
    Due to nuclear attractive force and electrostatic repulsion
    - Occasionally α tunnels out of nucleus

$$_{92}U^{238} \rightarrow {}_{90}Th^{234} + {}_{2}He^{4}$$

$$\uparrow \qquad\quad \uparrow$$

Daughter nucleus

- Disintegration $Q = (M_U - M_{Th} - M_\alpha)c^2$.
  - Sum of products < Uranium mass
    - Potential energy higher than α kinetic energy (energy of motion)
    - $\therefore$ energy released as KE of daughter particles
    - a shorter half-life corresponds to a higher KE for alpha

β decays L13p5

- ${}_6C^{14} \rightarrow {}_7N^{14} + e^-$ (?)
  - The number of nucleons constant, but atomic number changes by 1
  - particle emitted is electron which was not originally present in the nucleus. This suggestsed (and has been confirmed) that it arises from the transformation of a neutron into a proton + electron. This suggests that either the proton, or the neutron, is a composite (i.e. not fundamental) particle.

- If one body (C nucleus) is stationary and splits into two daughters, then each daughter must carry away the same amount of momentum but in opposite directions to each other.

  - but this is not observed. The electron is emitted with a broad range of energies and angles.
  - this appears to mean momentum conservation is not followed!
  - an undetected neutral particle, called the neutrino, was postulated

$$ {}_6C^{14} \rightarrow {}_7N^{14} + e^- + \bar{\nu} $$

  - Mass $m_\nu \approx 0$, $q = 0$
  - Interacts very weakly with matter: extremely Hard to detect

- Carbon dating
  - Cosmic rays cause nuclear reactions in upper atmosphere
  - C^{14} / C^{12} ratio constant
  - When organism dies: no longer takes in C^{14}, so ratio decreases with time $\tau \approx 5700$ years

Weak nuclear interaction

- the presence of beta decay suggests a process by which a neutron can 'turn into' a proton plus an electron
- this process happens very rarely. In other words, it is governed by a 'weak force' of some kind.
- the neutrino is a particle which only feels this force, since it has no charge, does not feel the strong nuclear interaction, and has almost no mass.
  - in fact, neutrino's only recently have been determined to have a mass at all. But they interact so little that it is still very hard to say what that mass actually is.

γ decays L13p6

A nucleus can be in an excited state

- Nucleons behaving sort of like electrons in an atom, they can be moving with more or less energy within the nucleus
    - Energy levels governed by quantum mechanics
    - Because strong force is so strong, these energy levels are much more complicated than electron energy levels of an atom

- Reduce energy level by emission of γ
    - λ much shorter than visible λ's
      $\sim 10^{-6}\ \lambda_{vis}$

- no change in Z, nor A of nucleus
    - just energy level of nucleus.

      ${}_5B^{12} \square {}_6C^{*12} + e^- + \bar{\nu}$.
      ${}_6C^{*12}\ \square + {}_6C^{12} + \gamma$.

Fission & Fusion L13p7

Fission

- splitting of one heavy nucleus into two or more relatively equal sized pieces

  - Uranium fission discovered, 1938-39
  - bombard U(235) nucleus with neutrons
  - combined mass of daughters < parent Uranium mass
    - therefore, energy is released

  - produces elements not found in nature (‘trans-uranium’ elements)
    - these are unstable nuclei
    - neutrons are emitted from these nuclei

  - chain reaction possible, because neutrons from trans-uranium elements can interact with other Uranium nuclei --> reaction spreads thru material

Fusion

- when combine two atomic nuclei into one, for instance, fusing two Hydrogen nuclei to form a Helium nucleus
  - o Protons must approach close enough to become He nucleus
    - Must overcome their electrostatic repulsion
  - o When fusing light nuclei, the resulting nucleus is less massive than the sum of the original nuclei: therefore energy produced
- Atoms lighter than Fe
  - o Can be combined to produce a more tightly bound nucleus

  - o $\therefore$ Loss of mass □ release of energy

    ${}_1H^1 + {}_1H^1$ □ ${}_1H^2 + e^+ + \nu.$
    ${}_1H^1 + {}_1H^2$ □ ${}_2He^3 + \gamma.$

Nuclear reactions

- atomic physics -> electromagnetic interactions -> chemistry -> visible light
- nuclear physics -> strong nuclear interactions -> nuclear reactions -> X-rays

Questions

1) Describe the Rutherford scattering experiment. How did this result clarify atomic structure? [10 pts]

2) From the point-of-view of a Particle in a Box scenario, explain how electrons in atoms are limited to specific energy levels. [10 pts]

3) State the Exclusion Principle. How does this relate to the problem of the stability of atoms? [10 pts]

4) What are the names of the two new forces inferred from nuclear physics? [4 pts]

5) Explain why one of the following processes occur: α (alpha) decay, β (beta) decay, γ (gamma) decay. [10 pts]

6) Explain how either fusion or fission generate energy. [10 pts]