DEVIL PHYSICS
THE BADDEST CLASS ON CAMPUS
IB PHYSICS

TSOKOS LESSON 12-2
NUCLEAR PHYSICS

Essential Idea:

- The idea of discreteness that we met in the atomic world continues to exist in the nuclear world as well.

Nature Of Science:

- Theoretical advances and inspiration: Progress in atomic, nuclear and particle physics often came from theoretical advances and strokes of inspiration.
- Advances in instrumentation: New ways of detecting subatomic particles due to advances in electronic technology were also crucial.

Nature Of Science:

- Modern computing power: Finally, the analysis of the data gathered in modern particle detectors in particle accelerator experiments would be impossible without modern computing power.

Theory Of Knowledge:

- Much of the knowledge about subatomic particles is based on the models one uses to interpret the data from experiments.
- How can we be sure that we are discovering an "independent truth" not influenced by our models?
- Is there such a thing as a single truth?

Understandings:

- Rutherford scattering and nuclear radius
- Nuclear energy levels
- The neutrino
- The law of radioactive decay and the decay constant

Applications And Skills:

- Describing a scattering experiment including location of minimum intensity for the diffracted particles based on their de Broglie wavelength
- Explaining deviations from Rutherford scattering in high energy experiments

Applications And Skills:

- Describing experimental evidence for nuclear energy levels
- Solving problems involving the radioactive decay law for arbitrary time intervals
- Explaining the methods for measuring short and long half-lives

Guidance:

- Students should be aware that nuclear densities are approximately the same for all nuclei and that the only macroscopic objects with the same density as nuclei are neutron stars
- The small angle approximation is usually not appropriate to use to determine the location of the minimum intensity

Data Booklet Reference:

- $R = R_0 A^{1/3}$
- $N = N_0 e^{-\lambda t}$
- $A = \lambda N_0 e^{-\lambda t}$
- $\sin\theta \approx \frac{\lambda}{D}$

Utilization:

- Knowledge of radioactivity, radioactive substances and the radioactive decay law are crucial in modern nuclear medicine

Aims:

- Aim 2: detection of the neutrino demonstrates the continuing growing body of knowledge scientists are gathering in this area of study

Scattering Experiments and Distance of Closest Approach

- An alpha particle of charge $q=+2e$ is fired head-on at a nucleus
- The particle's total energy is kinetic, $E=E_k$

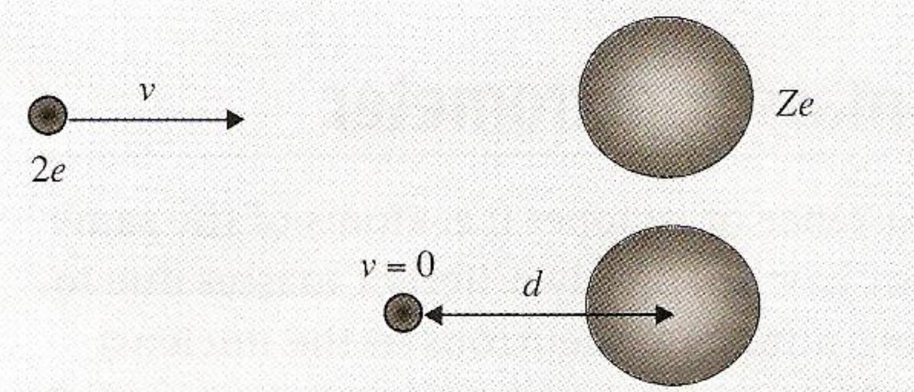


Figure 6.1 The closest approach of an alpha particle happens in a head-on collision.

Scattering Experiments and Distance of Closest Approach

- The particle is repelled by the positive charge of the nucleus

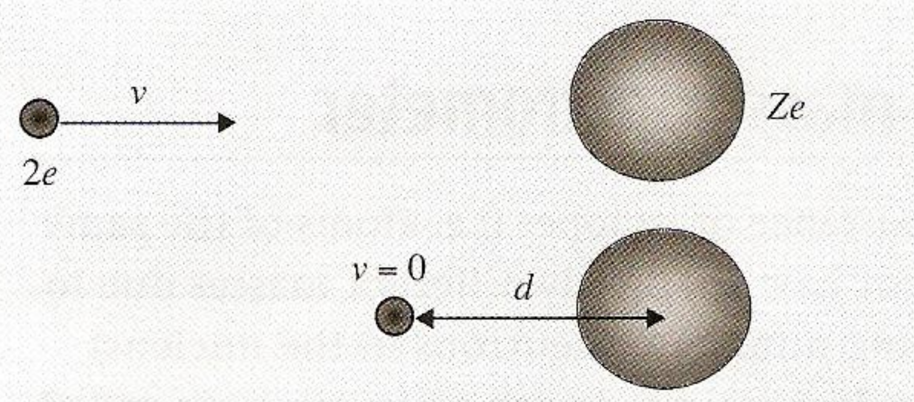


Figure 6.1 The closest approach of an alpha particle happens in a head-on collision.

Scattering Experiments and Distance of Closest Approach

- When the particle stops, all of its kinetic energy has been converted into potential energy

$$E = k\frac{Qq}{d}$$

$$E = k\frac{(Ze)(2e)}{d}$$

$$E = k\frac{2Ze^2}{d}$$

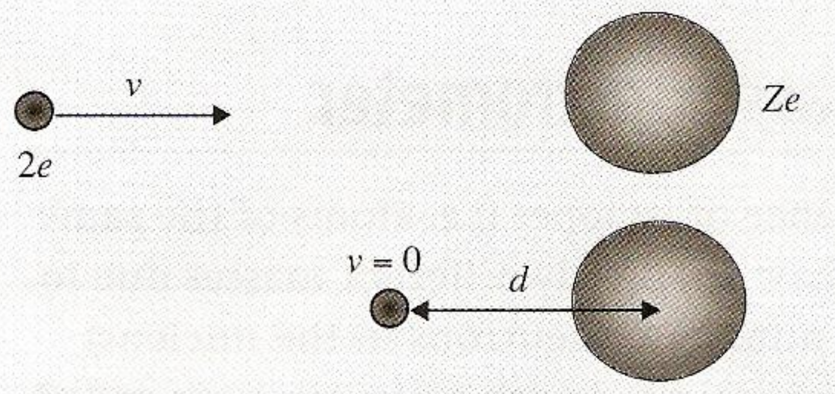


Figure 6.1 The closest approach of an alpha particle happens in a head-on collision.

Scattering Experiments and Distance of Closest Approach

- When the particle stops, all of its kinetic energy has been converted into potential energy

$$E_K = k\frac{2Ze^2}{d}$$

$$d = k\frac{2Ze^2}{E_K}$$

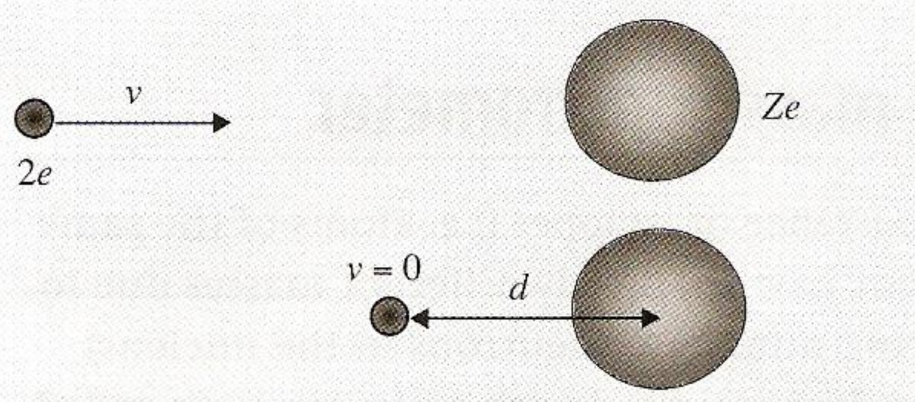


Figure 6.1 The closest approach of an alpha particle happens in a head-on collision.

Scattering Experiments and Distance of Closest Approach

- As kinetic energy of the alpha particle increases, distance decreases until the nuclear radius is reached and obtained

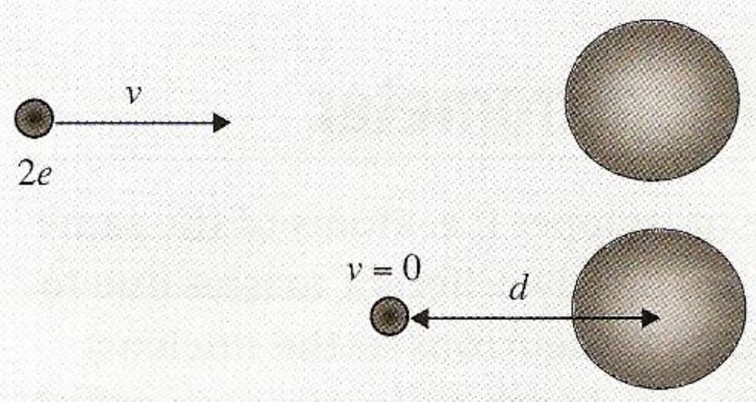


Figure 6.1 The closest approach of an alpha particle happens in a head-on collision.

$$E_K = k\frac{2Ze^2}{d}$$

$$d = k\frac{2Ze^2}{E_K}$$

Scattering Experiments and Distance of Closest Approach

- Rutherford Scattering
  - http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html
- Closest Approach to Nucleus
  - http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html
- Nuclear Radius Relationship
  - http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

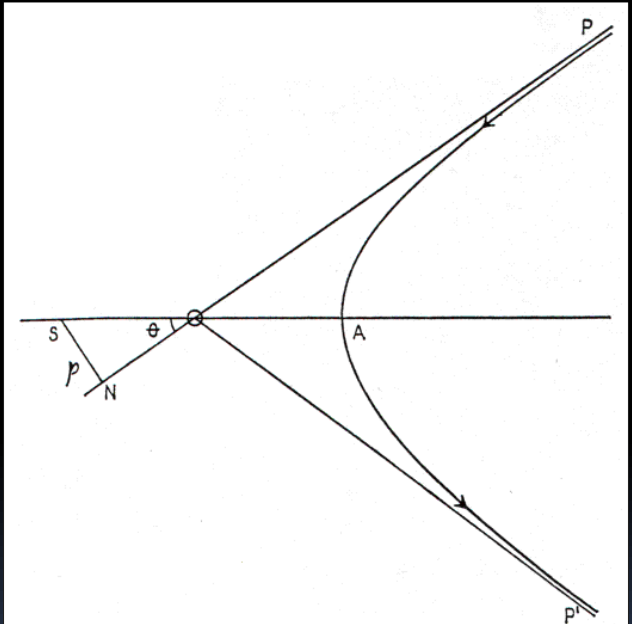


Fig. 1

Scattering Experiments and Distance of Closest Approach

- Further experiments have been able to refine the estimates for nuclear radii to be

$$R = 1.2 x A^{1/3} x 10^{-15} m$$

- ***What this also implies is that all nuclei have roughly the same density***

Scattering Experiments and Distance of Closest Approach

$$R = 1.2 x A^{1/3} x 10^{-15} m$$

- Data Guide:

$$R = R_0 x A^{1/3}$$

$$R_0 = 1.2 x 10^{-15} m$$

Diffraction Experiments

- If a particle has a deBroglie wavelength $\boldsymbol{\lambda}$ that is on the order of the diameter of a nucleus, it will diffract around it
- The diffraction angle will be where ***b*** is the diameter of the diffracting object

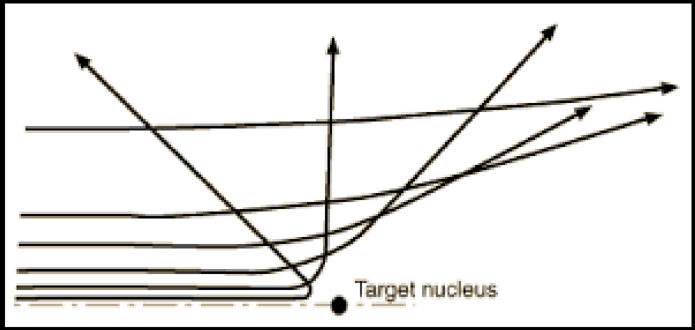
$$\sin\theta = \frac{\lambda}{b}$$

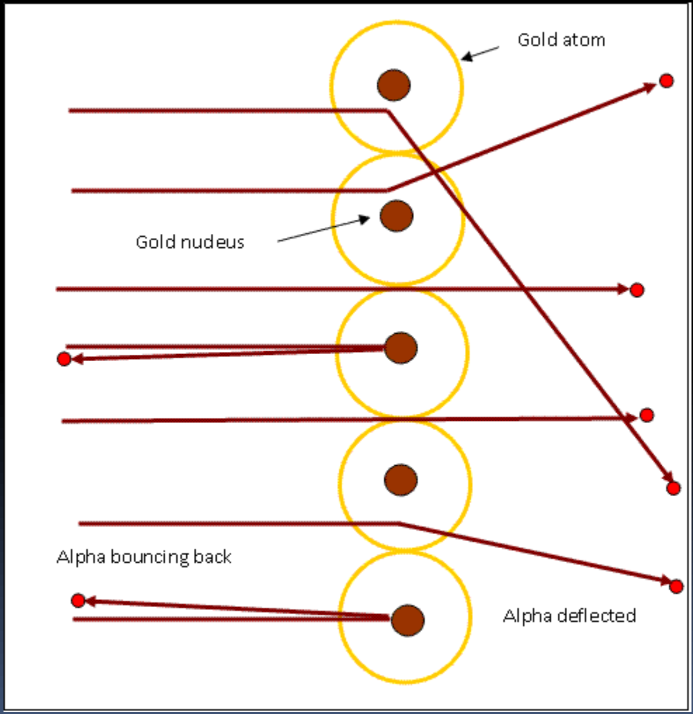
  - Electrons are used because they aren't affected by strong force
  - Neutrons used used because they aren't affected by electrical force

Deviations from Rutherford Scattering

- Rutherford derived a formula for scattering of alpha particles
- As the scattering angle increases, the number of particles at that angle decreases sharply

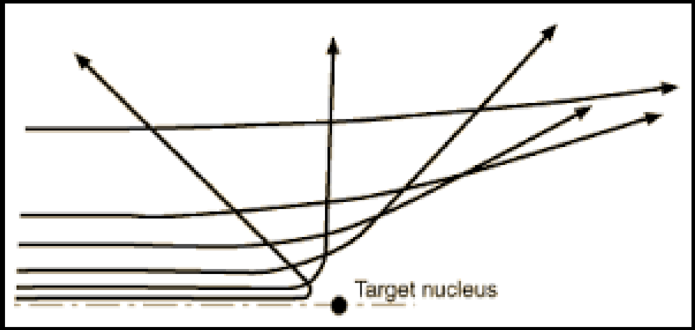
$$N \propto \frac{1}{\sin^4 \frac{\theta}{2}}$$

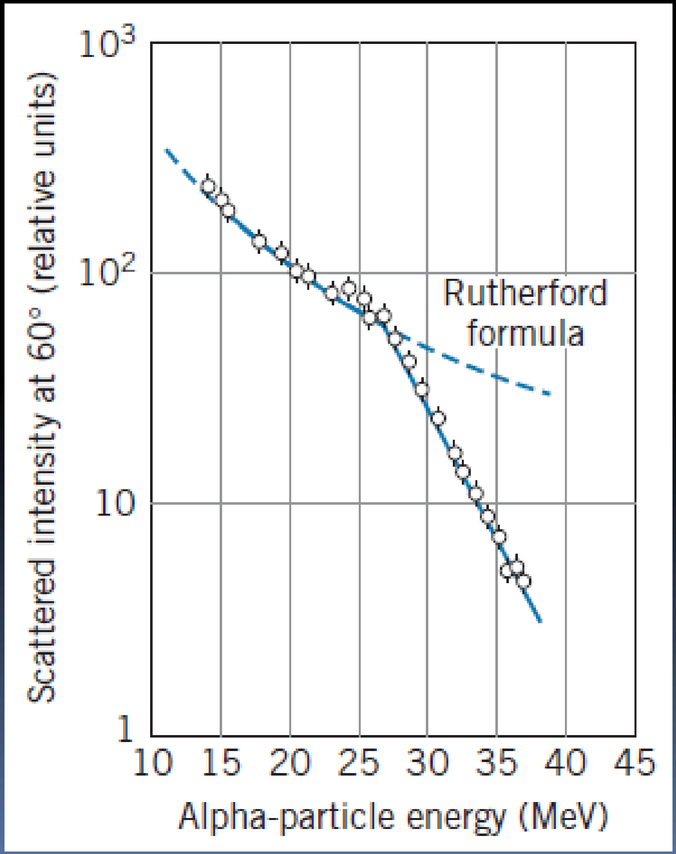




Deviations from Rutherford Scattering

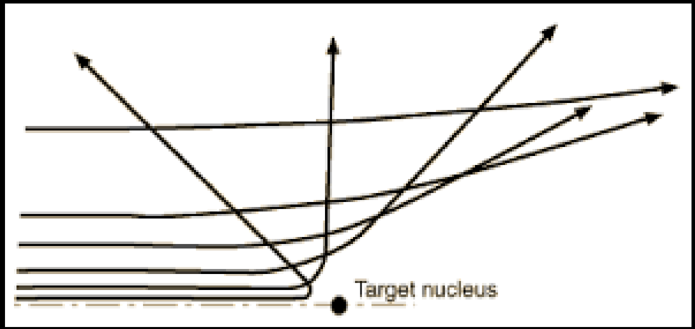
- However, with greater kinetic energy deviations in the Rutherford formula started occurring
- One of Rutherford's assumptions was that only the electrical repulsion force acted on the alpha
- *Is that a valid assumption?*

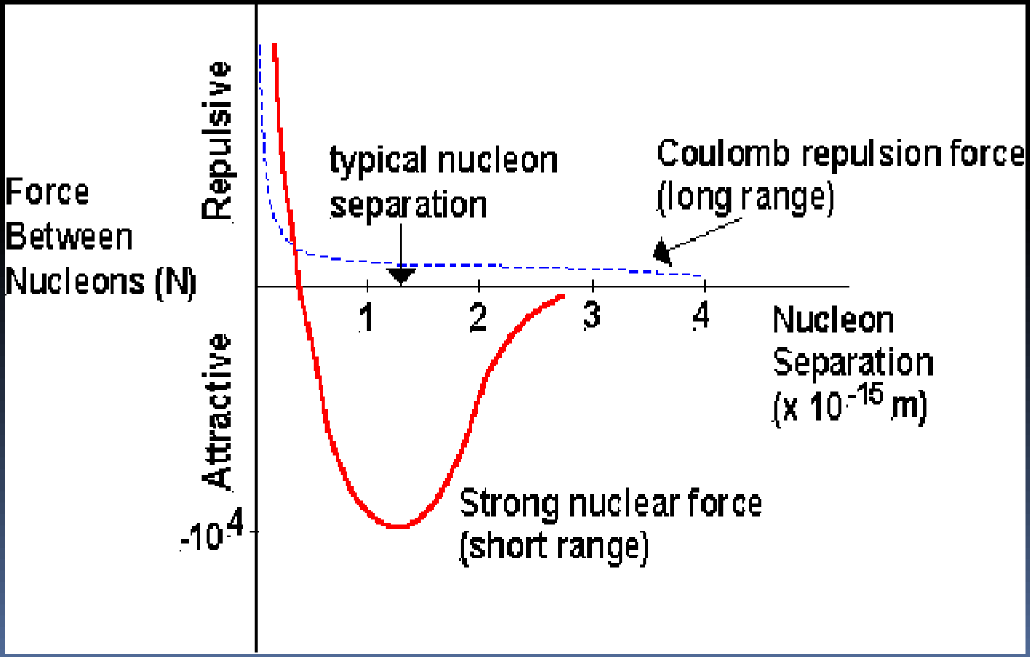


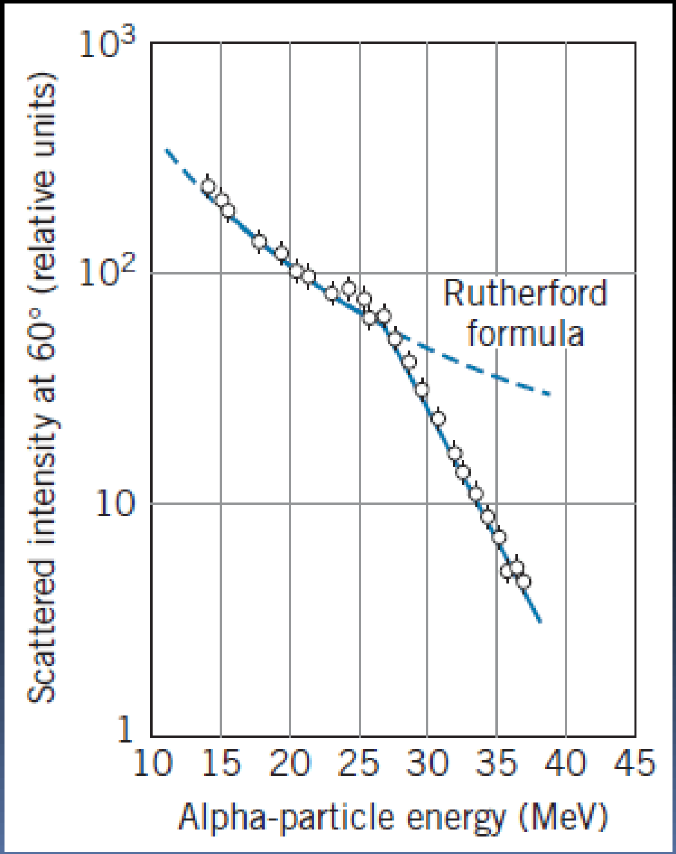


Deviations from Rutherford Scattering

- No, at distances of less than about 10^{-15} m, the strong force interacts with the alpha particle







Nuclear Energy Levels

- The nucleus, like the atom, exists in discrete energy levels
- Main evidence is that alpha particles and gamma ray photons are emitted in discrete energy levels during decays
- In beta decays, the electrons have a continuous range of energies

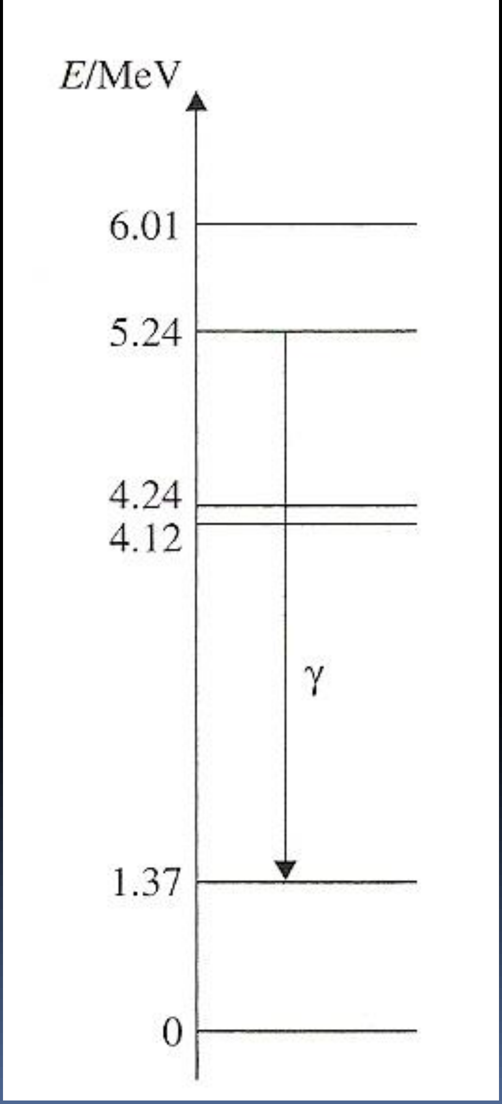
Nuclear Energy Levels

- Nuclear energy levels of

$$^{24}_{12}Mg$$

- Shown is a gamma decay (release of a photon) with energy

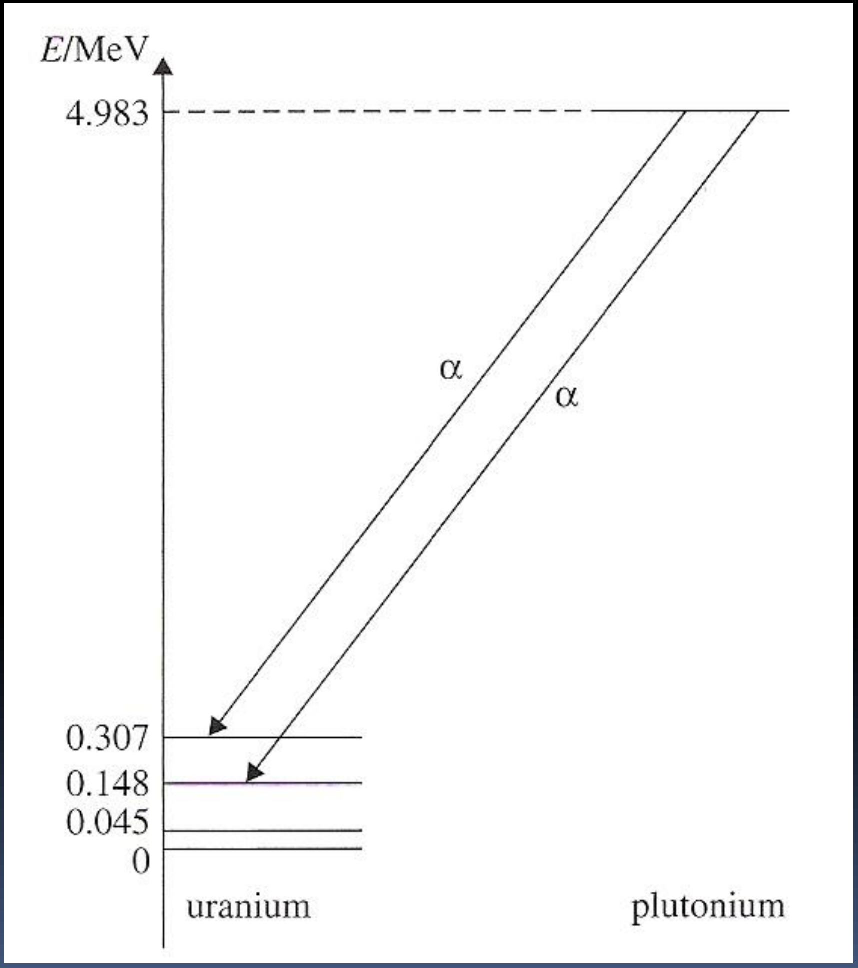
$$5.24 - 1.37 = 3.87 MeV$$



Nuclear Energy Levels

- Two decays of plutonium into uranium with release of an alpha particle

$$^{242}_{94}Pu \rightarrow ^{238}_{92}U + ^{4}_{2}\alpha$$



Beta Decay and the Neutrino

- Decay of a neutron
  - Decays into a proton, electron, and an antineutrino

$$ {}_{0}^{1}n \rightarrow {}_{1}^{1}p + {}_{-1}^{0}e + {}_{0}^{0}\overline{\nu}_{e} $$

  - This happens to free neutrons outside the nucleus because neutrons have greater mass than protons
  - Half-life is about 11 minutes

Beta Decay and the Neutrino

- Decay of a proton
  - Decays into a neutron with the emission of a positron (anti-particle of an electron) and a neutrino

$$ {}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e + {}^{0}_{0}v_{e} $$

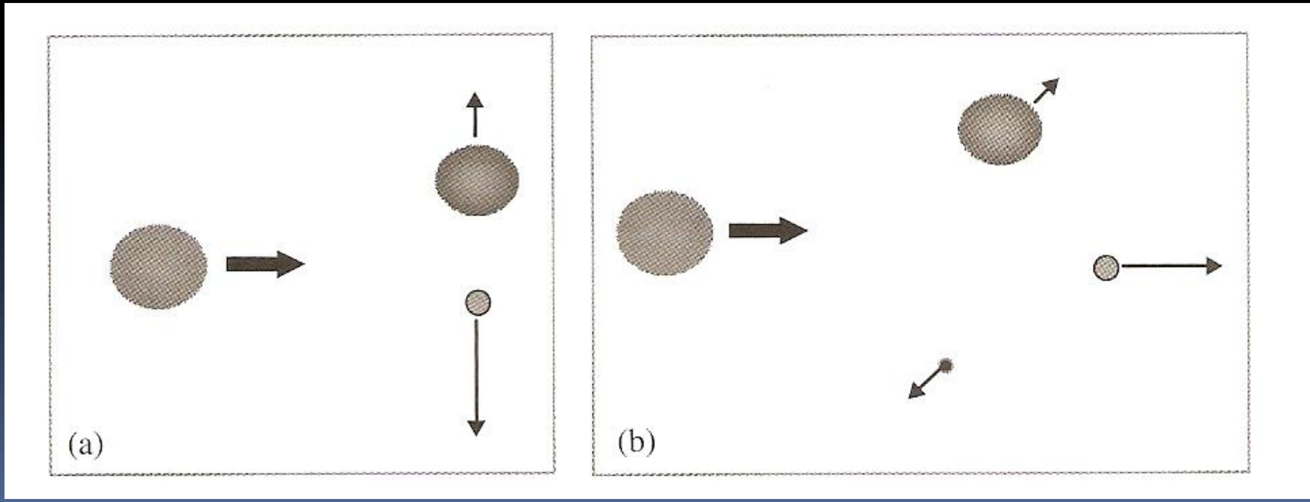
  - Decay occurs inside the nucleus where binding energy makes up for the mass difference
  - Not a split, but a disappearance and reformation

Beta Decay and the Neutrino

- Presence of neutrinos predicted because the mass of a neutron is greater than the sum of the mass of a proton and electron

$$ {}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + {}^{0}_{0}\overline{\nu}_e $$

$$ {}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e + {}^{0}_{0}\nu_e $$

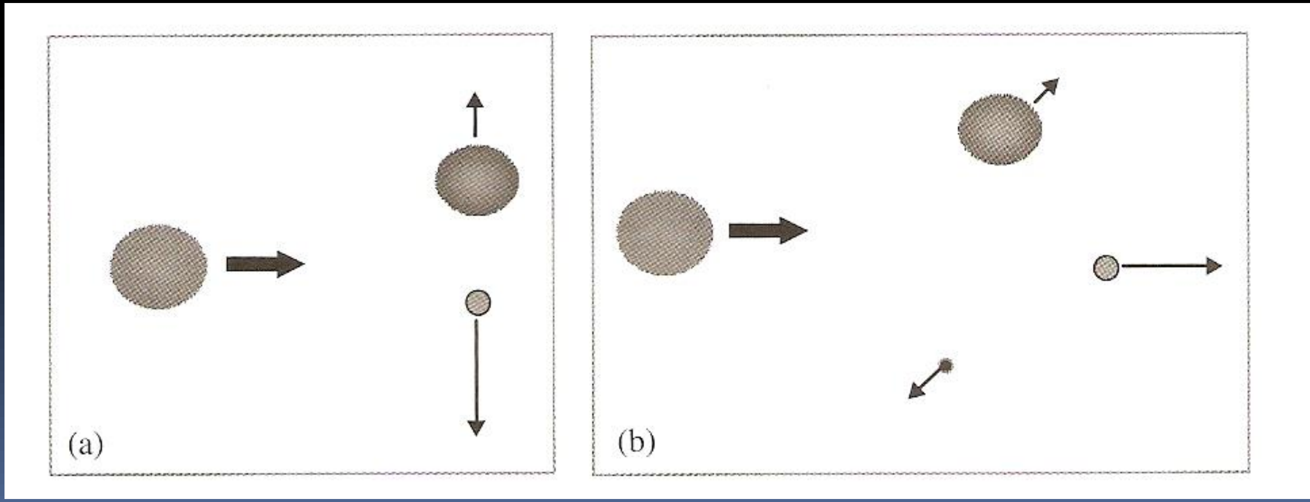


Beta Decay and the Neutrino

- In other decays, this mass difference showed up in kinetic energy of the particles

$$^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + {}^{0}_{0}\bar{\nu}_e$$

$$^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e + {}^{0}_{0}\nu_e$$

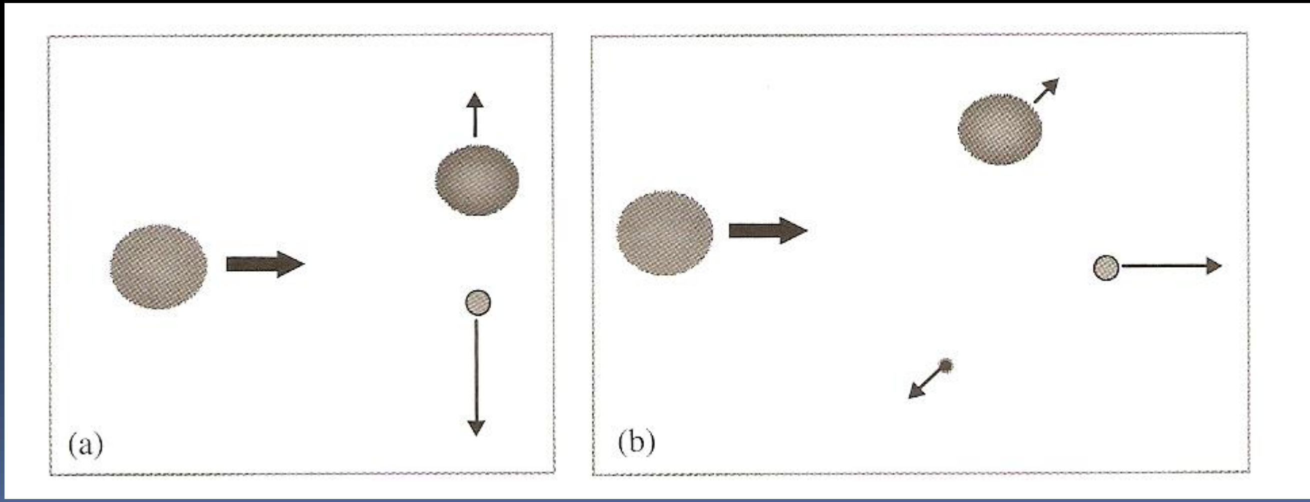


Beta Decay and the Neutrino

- Absence of the kinetic energy led to experiments that uncovered the neutrino (little neutral one) in 1953

$$^{1}_{0}n \rightarrow ^{1}_{1}p + ^{0}_{-1}e + ^{0}_{0}\overline{v}_{e}$$

$$^{1}_{1}p \rightarrow ^{1}_{0}n + ^{0}_{+1}e + ^{0}_{0}v_{e}$$



Beta Decay and the Neutrino

- Electron Capture
  - A proton inside the nucleus captures an electron and turns into a neutron and neutrino

$$ {}^{1}_{1}p + {}^{0}_{-1}e \rightarrow {}^{1}_{0}n + {}^{0}_{0}\nu_e $$

  - This is the process occurring in neutron stars
  - Huge pressure inside the star drives electrons into protons, turning them into neutrons

Beta Decay and the Neutrino

- Examples of Beta Decay

$${}_{0}^{1}n \rightarrow {}_{1}^{1}p + {}_{-1}^{0}e + {}_{0}^{0}\overline{\nu}_{e}$$

$${}_{1}^{1}p \rightarrow {}_{0}^{1}n + {}_{+1}^{0}e + {}_{0}^{0}\nu_{e}$$

$${}_{1}^{1}p + {}_{-1}^{0}e \rightarrow {}_{0}^{1}n + {}_{0}^{0}\nu_{e}$$

Decay	Half-life	Maximum energy
${}_{1}^{3}H \rightarrow {}_{2}^{3}He + {}_{-1}^{0}e + {}_{0}^{0}\bar{\nu}_e$	12.3 yr	0.0186 MeV
${}_{6}^{14}C \rightarrow {}_{7}^{14}N + {}_{-1}^{0}e + {}_{0}^{0}\bar{\nu}_e$	5730 yr	0.156 MeV
${}_{11}^{22}Na \rightarrow {}_{10}^{22}Ne + {}_{+1}^{0}e + {}_{0}^{0}\nu_e$	2.60 yr	0.546 MeV
${}_{7}^{13}N \rightarrow {}_{6}^{13}C + {}_{+1}^{0}e + {}_{0}^{0}\nu_e$	9.99 min	1.19 MeV

Radioactive Decay Law

- The number of nuclei that will decay per second is proportional to the number of atoms present that have not yet decayed

$$\frac{dN}{dt} = -\lambda N$$

- λ is a constant known as the decay constant
- Represents the probability of decay per unit time

Radioactive Decay Law

- The number of undecayed nuclei ***N*** at any given time in relation to the original number of undecayed nuclei N_0 is given by the equation,

$$N = N_0 e^{-\lambda t}$$

- The decay rate is exponential

Radioactive Decay Law

- **Half-Life**: the time it takes for half of an amount of undecayed substance to decay
- The derivation to the right gives the relationship between half-life and decay rate

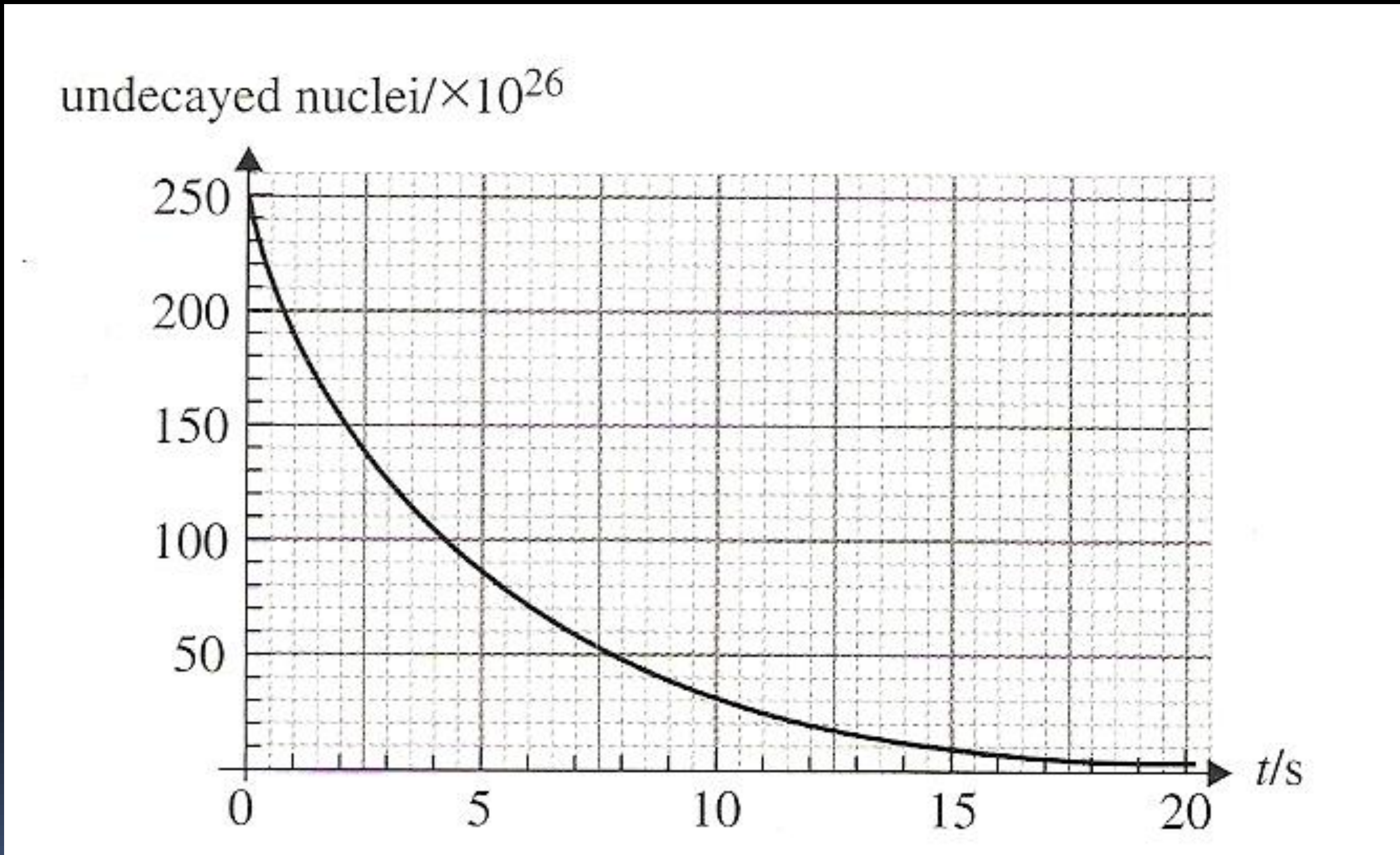
$$N = N_0 e^{-\lambda t}$$

$$\frac{N_0}{2} = N_0 e^{-\lambda T_{1/2}}$$

$$\ln\frac{1}{2} = \ln\left(e^{-\lambda T_{1/2}}\right)$$

$$0.693 = \lambda T_{1/2}$$

Radioactive Decay Law



Radioactive Decay Law

- The number of decays per second is called the ***activity***,
- The initial activity is

$$N = N_0 e^{-\lambda t}$$

$$A = -\frac{dN}{dt}$$

$$A = (N_0 \lambda) e^{-\lambda t}$$

$$A_0 = N_0 \lambda$$

$$A = \lambda N_0 e^{-\lambda t}$$

Radioactive Decay Law

- The decay constant represents the probability of decay per unit time

$$\frac{dN}{dt} = -\lambda N$$

$$dN = -\lambda N dt$$

$$probability = \frac{dN}{N} = -\lambda dt$$

$$\frac{probability}{dt} = \lambda$$

Essential Idea:

- The idea of discreteness that we met in the atomic world continues to exist in the nuclear world as well.

Understandings:

- Rutherford scattering and nuclear radius
- Nuclear energy levels
- The neutrino
- The law of radioactive decay and the decay constant

Guidance:

- Students should be aware that nuclear densities are approximately the same for all nuclei and that the only macroscopic objects with the same density as nuclei are neutron stars
- The small angle approximation is usually not appropriate to use to determine the location of the minimum intensity

Data Booklet Reference:

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- $\sin \theta \approx \frac{\lambda}{D}$

QUESTIONS?

Homework

#24-40

[Radioactive Video]