Nuclear Physics

Michael Brodskiy
Professor: Q. Yan

April 13, 2023

Contents

1 Nuclear Structure

- The size of an atom is 1[Å]
- The size of the nucleus is .001[Å], or 1[fm]
- The repulsive positive charges in the nucleus are held together by the strong nuclear force
  - Has a very short range
- Protons have a charge of e^+ and a spin of $\frac{1}{2}$, neutrons have no charge, but the same spin value
- Neutrons were discovered in 1932
- The atomic number is the sum of protons and neutrons
  - Thus, a nucleus with a mass number A contains Z protons and $N = A - Z$ neutrons
  - Neutrons and protons are referred to as nucleons
  - Nuclei with similar Z may have different N
  - For example, fully specifying a hydrogen atom, we may get:
    * ${}^1_1H_0$
    * ${}^2_1H_1$
    * ${}^3_1H_2$
  - These are known as isotopes

2 Nuclear Size and Shape

- It is observed that the density of a nucleus does not depend on its atomic number A

$$\frac{N+Z}{\frac{4}{3}\pi R^2} \Rightarrow \frac{A}{R^2} \quad \text{is constant}$$

- The Nucleus Radius
  - We know $R = R_o A^{\frac{1}{3}}$
  - We also know $\rho = \frac{m}{V}$
  - Combining these, we get
- Nuclear Binding Energy

- $E_b = \left[Nm_n + Zm_p - m\left({}^{A}_{Z}Z_N\right)\right]$
- $\frac{E_b}{A} = \frac{\text{Binding energy}}{\#\text{ of molecules}}$
- The binding energy to remove the least bound nucleon from the nucleus is on the order of [MeV], while the ionization energy of an electron is on the order of [eV]

- Stable and Unstable Nuclei
  - Most nuclei are not stable
  - They decay to lighter, more stable ones
  - Decay Processes:
    * $\alpha-$decay — Emission of a helium nucleus, ${}^{4}_{2}He_2$
    * $\beta-$decay — Involves the ejection of a beta particle $\rightarrow {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X' + e^- + \beta$ or ${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}X' + e^+ + \beta$
  - Activity and Decay Probabilities
    * This is the rate at which N unstable nuclei decay
    * Number of decays per second
    * Units of Curies are used $(1[\text{Ci}] = 3.7 \cdot 10^{10}[\text{decays/s}])$
    * $P(t)$ is the probability of decay after a given time t
    * Decay probability per nucleus per second is called the decay constant, λ
    * λ is decay process/element dependent
    * The activity, a, would be $a = \lambda N$
  - Exponential Law of Radioactive Decay:
    * $a = -\frac{dN}{dt} \Rightarrow \lambda N = -\frac{dN}{dt}$
    * Solving this yields $N = N_o e^{-\lambda t}$
    * This means $a = a_o e^{-\lambda t}$

- Particles
  - Spin 1/2, tiny mass, no charge: neutrinos
  - An anti-neutrino is indicated by $n \rightarrow p$