CBE 30235: Introduction to Nuclear Engineering
Problem Set 1: Atomic Structure and Binding Energy

Due: Friday, January 23, 2026 (via GradeScope at Midnight)

Problem 1: Nuclear Density of a Pulsar

Experimental data suggests that the nuclear radius follows the relationship $R \approx R_0 A^{1/3}$ where $R_0 \approx 1.25$ fm. A neutron star is a macroscopic object composed almost entirely of neutrons ($m_n \approx 1.675 \times 10^{-27}$ kg).

Calculate the radius (in kilometers) of a neutron star that has a mass equal to 1.4 solar masses ($1M_\odot \approx 1.989 \times 10^{30}$ kg). **Assume the neutron star has the same constant density as an atomic nucleus.**

Problem 2: Mass Defect and the Neutral Atom Convention

Calculate the Total Binding Energy (BE) in MeV and the Binding Energy per Nucleon (E_b) in MeV/nucleon for the alpha particle, ${}^4_2$He.

- Use the following neutral atom mass data: $M(^4\text{He}) = 4.002603$ u, $M(^1\text{H}) = 1.007825$ u, and neutron mass $m_n = 1.008665$ u.
- Conversion: 1 u = 931.5 MeV/c^2.
- **Conceptual Question:** Explain why we use the hydrogen mass $M(^1\text{H})$ instead of the bare proton mass m_p in this calculation. What happens to the electron masses?

Problem 3: The Physics of Technetium-99m

A patient undergoes a myocardial perfusion scan using ^{99m}Tc. The nucleus relaxes from its metastable state by emitting a 140.5 keV gamma ray.

(a) Calculate the wavelength (λ) of the emitted gamma photon in picometers (pm).

(b) Calculate the recoil energy (E_r) of the ^{99}Tc nucleus in eV. Recall that for a photon, $p = E/c$, and for the nucleus, $E_r = p^2/2M$. (Use $M \approx 99$ u).

(c) **Comparison:** Typical chemical bond energies are in the range of 2–5 eV. Is the recoil energy calculated in part (b) sufficient to break a chemical bond holding the Technetium atom in a pharmaceutical molecule?

Problem 4: Trends in the Valley of Stability

Using the Chart of the Nuclides (or Appendix II in Lamarsh), determine the N/Z ratio for the following stable isotopes: ^{12}C, ^{56}Fe, and ^{208}Pb.

In 2–3 sentences, describe the physical reason why the N/Z ratio must increase as Z increases to maintain stability. (Hint: Consider the range and nature of the two competing forces inside the nucleus).

Problem 5: The Energy of the "Lonely Neutron"

A free neutron is unstable and decays via beta emission ($n \rightarrow p + e^- + \bar{\nu}_e$). Show that this decay is energetically possible by calculating the Q-value (energy released) in MeV.

- Use: $m_n = 1.008665$ u and $M(^1\mathrm{H}) = 1.007825$ u.
- Assume the antineutrino is massless.
- *Tip: Be careful with the electron mass. Does using $M(^1H)$ account for the electron created in the decay?*