Georgia Institute of Technology

The George W. Woodruff School of Mechanical Engineering
Nuclear & Radiological Engineering/Medical Physics Program

Ph.D. Qualifier Exam

Spring Semester 2008

_______________ Your ID Code

Radiation Physics (Day 1)

Instructions

1. Use a separate page for each answer sheet (no front to back answers).
2. The question number should be shown on each answer sheet.
3. ANSWER 4 OF 6 QUESTIONS ONLY.
4. Staple your question sheet to your answer sheets and turn in.

NRE/MP Radiation Physics

Answer any 4 of the following 6 questions.

1. Discuss the neutron fission reaction. Why do only the heaviest (largest atomic mass #) nuclei undergo fission with energy release when bombarded with neutrons? Why do some heavy nuclei undergo fission when bombarded with low energy (thermal) neutrons, and others do not? Explain “delayed neutron” release in fission. What is the amount of energy released in the thermal neutron induced fission of a U-235 nucleus? What is the average number of neutrons released in the thermal neutron induced fission of a nucleus of U-235?

2. Consider the case that a thermal neutron is captured by a ground-state ^{59}Co to form an excited ^{60}Co nucleus. Use Attachment A to answer the following questions: (a) What energy, measured from the ground state of ^{60}Co, is the excited state? (b) What is the most likely I^{π} for the excited state?

Attachment A

TABLE OF NUCLEAR PROPERTIES

The following table shows some properties of a selection of isotopes. For each element only the stable and relatively long-lived radioactive isotopes are included. Ground-state atomic masses and spin-parity assignments are shown for all isotopes; uncertain spin-parity assignments are in parentheses. Abundances are given for stable isotopes, and for radioactive isotopes the half-life and principal decay mode are shown (ε—electron capture, possibly including positron emission; β^-—negative beta decay; α—alpha decay; f—spontaneous fission). The masses are those of the corresponding neutral atoms and were taken from the 1983 atomic mass evaluation: A. H. Wapstra and G. Audi, *Nucl. Phys.* **A432**, 1 (1985). In the half-life entries, My = 10^6 y. Uncertainties in the masses are typically 10^{-5} u (10^{-4} u for some cases far from stability); uncertainties in the abundances and half-lives are typically at or below the level of the last digit tabulated.

	Z	A	Atomic mass (u)	I^π	*Abundance* or Half-life
H	1	1	1.007825	$\frac{1}{2}^+$	*99.985%*
		2	2.014102	1^+	*0.015%*
		3	3.016049	$\frac{1}{2}^+$	12.3 y (β^-)
He	2	3	3.016029	$\frac{1}{2}^+$	*1.38×10^{-4}%*
		4	4.002603	0^+	*99.99986%*
Li	3	6	6.015121	1^+	*7.5%*
		7	7.016003	$\frac{3}{2}^-$	*92.5%*
		8	8.022486	2^+	0.84 s (β^-)
Be	4	7	7.016928	$\frac{3}{2}^-$	53.3 d (ε)
		8	8.005305	0^+	0.07 fs (α)
		9	9.012182	$\frac{3}{2}^-$	*100%*
		10	10.013534	0^+	1.6 My (β^-)
		11	11.021658	$\frac{1}{2}^+$	13.8 s (β^-)

	Z	A	Atomic mass (u)	I^π	*Abundance* or Half-life
Co	27	54	53.948460	0^+	0.19 s (ε)
		55	54.942001	$\frac{7}{2}^-$	17.5 h (ε)
		56	55.939841	4^+	78.8 d (ε)
		57	56.936294	$\frac{7}{2}^-$	271 d (ε)
		58	57.935755	2^+	70.8 d (ε)
		59	58.933198	$\frac{7}{2}^-$	*100%*
		60	59.933820	5^+	5.27 y (β^-)
		61	60.932478	$\frac{7}{2}^-$	1.65 h (β^-)
		62	61.934060	2^+	1.5 m (β^-)
		63	62.933614	$(\frac{7}{2})^-$	27.5 s (β^-)

3. The first resonance of neutron cross section for ^{16}O is observed at E_n = 443 keV in the laboratory system. (a) What energy, measured from the ground state of ^{17}O, is the excited state which gives rise to the above resonance? (b) If the total width (Γ) of the resonance is 41 keV, what is the most probable reaction type of this resonance? e.g. (n,γ), elastic, inelastic),..etc. Why? (c) Will the Doppler Broadening effect (due to elevated temperatures) significantly change neutron interaction probabilities in the energy range of the resonance? Why or why not?

4. In many cases the decay of radionuclides is accompanied by the creation of new ones, either from the decay of a parent or from production by nuclear reactions such as cosmic ray interactions in the atmosphere or from neutron interactions in a nuclear reactor.
   a) If $Q(t)$ is the rate at which the radionuclide of interest is being created, write the general form of the expression for the variation of the number of the radionuclide atoms with time N(t). Assume that N_0 atoms are present at time t=0.
   b) Evaluate the general expression for the case of a constant rate of production of the radionuclide, namely, $Q(t) = Q_0$.

5. The fact that particles can behave like waves and that electromagnetic waves can behave like particles seems like a paradox. The de Broglie wavelength of an entity can resolve this paradox.
   a) Explain this statement using quantitative expressions wherever possible.
   b) What is the kinetic energy and velocity of a neutron with a de Broglie wavelength of 10^{-1} nanometers?
   c) Is this a thermal neutron?

6. Use the Bethe's stopping-power formula to calculate the collisional stopping power $(dE/dx)_c$ of: (a) a 1-MeV proton slowing down in aluminum, and (b) a 1-MeV electron slowing down in aluminum.

Appendix to Radiation Physics Qualifiers

Bethe's Stopping Power formula for heavy particles,

$$(-\frac{dE}{dx})_{coll} = \frac{4\pi k_0^2 z^2 e^4 n}{m_e c^2 \beta^2} (\ln \frac{2 m_e c^2 \beta^2}{I(1-\beta^2)} - \beta^2)$$

Bethe's Stopping Power formula for light particles,

$$(-\frac{dE}{dx})_{coll} = \frac{4\pi k_0^2 z^2 e^4 n}{m_e c^2 \beta^2} [\ln \frac{mc^2 \tau \sqrt{\tau+2}}{\sqrt{2} I} + F(\beta)]$$

and $F(\beta) = \frac{1-\beta^2}{2}[1 + \frac{\tau^2}{8} - (2\tau+1)\ln(2)]$.

In this formula,

k_0 = Coulomb force constant = $\frac{1}{4\pi\epsilon_0}$,

z = atomic number of the heavy particle,

e = magnitude of electronic charge,

n = number of electrons per unit volume in the medium,

m_e = electron rest mass,

c = speed of light in vacuum,

β = speed of particle relative to the speed of light

I = mean excitation energy of the medium

$\tau = T/m_e c^2$ being the kinetic energy (T) of the particle expressed in multiples of the rest energy ($m_e c^2$).

Mean Excitation Energy

I = {19.0 eV} for Z = 1,

I = {11.2 + 11.7 Z eV} for $2 \leq Z \leq 13$

I = {52.8 + 8.71 Z eV} for Z > 13

Note that,

$$\frac{4\pi k_0^2 z^2 e^4 n}{m_e c^2 \beta^2} = 8.12\times10^{-42} \frac{z^2 n}{\beta^2} J\, m^{-1} = 5.08\times10^{-31} \frac{z^2 n}{\beta^2} MeV\, cm^{-1}$$

Appendix A

Physical Constants

Planck's constant, $h = 6.6261 \times 10^{-34}$ J s
$\hbar = h/2\pi = 1.0546 \times 10^{-34}$ J s
Electron charge, $e = -1.6022 \times 10^{-19}$ C $= -4.8033 \times 10^{-10}$ esu
Velocity of light in vacuum, $c = 2.997925 \times 10^{8}$ m s^{-1}
Avogadro's number, $N_0 = 6.0221 \times 10^{23}$ mole^{-1}
Molar volume at STP (0°C, 760 torr) = 22.414 L
Density of air at STP (0°C, 760 torr) = 1.293 kg m^{-3}
= 1.293×10^{-3} g cm^{-3}
Rydberg constant, $R_\infty = 1.09737 \times 10^{7}$ m^{-1}
First Bohr orbit radius in hydrogen, $a_0 = 5.2918 \times 10^{-11}$ m
Ratio proton and electron masses = 1836.15
Electron mass, m = 0.00054858 AMU = 0.51100 MeV = 9.1094×10^{-31} kg
Proton mass = 1.0073 AMU = 938.27 MeV = 1.6726×10^{-27} kg
H atom mass = 1.0078 AMU = 938.77 MeV = 1.6735×10^{-27} kg
Neutron mass = 1.0087 AMU = 939.57 MeV = 1.6749×10^{-27} kg
Alpha-particle mass = 4.0015 AMU = 3727.4 MeV = 6.6447×10^{-27} kg
Boltzmann's constant, $k = 1.3807 \times 10^{-23}$ J K^{-1}

Principal source: E. R. Cohen and B. N. Taylor, "The Fundamental Physical Constants," *Physics Today* **47** (No. 8, Part 2), pp. 9–13, August (1994).

Appendix **B**

Units and Conversion Factors

1 cm = 10^4 μm = 10^8 Å
1 in. = 2.54 cm (exactly)
1 barn = 10^{-24} cm^2
1 L = 1 dm^3 = 10^{-3} m^3
1 dyne = 1 g cm s^{-2} = 10^{-5} kg m s^{-2} = 10^{-5} N
1 kg = 2.205 lb
1 erg = 1 dyne cm = 1 g cm^2 s^{-2} = 1 esu^2 cm^{-1}
1 J = 1 N m = 1 kg m^2 s^{-2} = 1.11265 × 10^{-10} C^2 m^{-1}
10^7 erg = 1 J
1 eV = 1.6022 × 10^{-12} erg = 1.6022 × 10^{-19} J
1 AMU = 931.49 MeV = 1.6605 × 10^{-27} kg
1 gram calorie = 4.186 J
1 W = 1 J s^{-1} = 1 V A
1 statvolt = 299.8 V
1 esu = 3.336 × 10^{-10} C
1 A = 1 C s^{-1}
1 C = 1 V F
1 Ci = 3.7 × 10^{10} s^{-1} = 3.7 × 10^{10} Bq (exactly)
1 R = 2.58 × 10^{-4} C kg^{-1} air (= 1 esu cm^{-3} air at STP)
1 rad = 100 erg g^{-1} = 0.01 Gy
1 Gy = 1 J kg^{-1} = 100 rad
1 Sv = 100 rem
0°C = 273 K
1 atmosphere = 760 mm Hg = 760 torr = 101.3 kPa
1 day = 86,400 s
1 yr = 365 days = 3.1536 × 10^7 s
1 radian = 57.30°