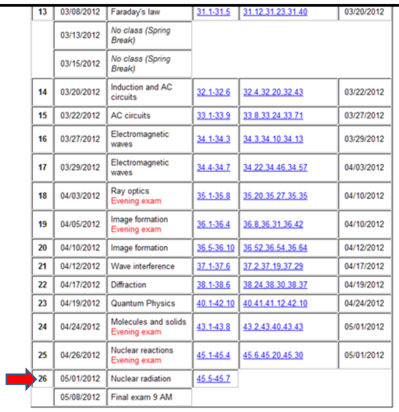
PHY 114 A General Physics II
11 AM-12:15 PM TR Olin 101

Plan for Lecture 26 (Chapter 45):

Some topics in nuclear physics

1. **Nuclear reactions**
2. **Fusion reactors**
3. **Fission reactors**

Link to NCSU Professor Wesley Henderson's course materials on "Engineering Challenges at the Energy Frontier“ (includes fission reactors) http://www.che.ncsu.edu/ILEET/CHE596web_Fall2011/index.html

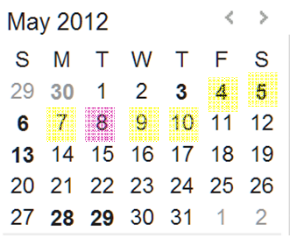


13	03/08/2012	Faraday's law	31.1-31.5	31.12,31.23,31.40	03/20/2012
	03/13/2012	*No class (Spring Break)*			
	03/15/2012	*No class (Spring Break)*			
14	03/20/2012	Induction and AC circuits	32.1-32.6	32.4,32.20,32.43	03/22/2012
15	03/22/2012	AC circuits	33.1-33.9	33.8,33.24,33.71	03/27/2012
16	03/27/2012	Electromagnetic waves	34.1-34.3	34.3,34.10,34.13	03/29/2012
17	03/29/2012	Electromagnetic waves	34.4-34.7	34.22,34.46,34.57	04/03/2012
18	04/03/2012	Ray optics Evening exam	35.1-35.8	35.20,35.27,35.35	04/10/2012
19	04/05/2012	Image formation Evening exam	36.1-36.4	36.8,36.31,36.42	04/10/2012
20	04/10/2012	Image formation	36.5-36.10	36.52,36.54,36.64	04/12/2012
21	04/12/2012	Wave interference	37.1-37.6	37.2,37.19,37.29	04/17/2012
22	04/17/2012	Diffraction	38.1-38.6	38.24,38.30,38.37	04/19/2012
23	04/19/2012	Quantum Physics	40.1-42.10	40.41,41.12,42.10	04/24/2012
24	04/24/2012	Molecules and solids Evening exam	43.1-43.8	43.2,43.40,43.43	05/01/2012
25	04/26/2012	Nuclear reactions Evening exam	45.1-45.4	45.6,45.20,45.30	05/01/2012
26	05/01/2012	Nuclear radiation	45.5-45.7		
	05/08/2012	Final exam 9 AM			

General comments on final exam:
- It will be comprehensive
- May bring up to 4 equation sheets (turned in with exam papers)
- Need calculator; must not use cell phone, computer, etc.
- May pick up final exams from my office after they are graded

A PHY 114 review session has tentatively been scheduled for Thursday 5/3/2012 at 11 AM in Olin 107

A. I plan to come
B. I do not plan to come
C. Other suggestions?



May 2012

S	M	T	W	T	F	S
29	30	1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30	31	1	2

▨ Other exams

▨ PHY114 A

NOTE: Students should have no more than two exams in a 24-hour period. They should be allowed to reschedule exams in excess of two in a 24-hour period.

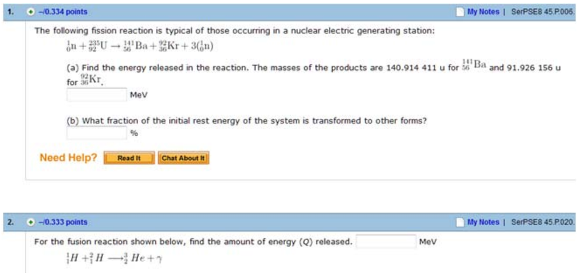
How many of you need to reschedule the final exam time:

A. Happy to take the exam as scheduled (May 8)
B. Entitled to reschedule according to WFU policy
C. Not entitled, but would prefer to reschedule

For those of you who need/would like to reschedule – which time is likely to be preferable

A. Prefer rescheduled time *earlier* than May 8
B. Prefer rescheduled time *later* than May 8

Webassign comments:



1. –/0.334 points

The following fission reaction is typical of those occurring in a nuclear electric generating station:

$${}^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3({}^{1}_{0}\mathrm{n})$$

(a) Find the energy released in the reaction. The masses of the products are 140.914 411 u for ${}^{141}_{56}\mathrm{Ba}$ and 91.926 156 u for ${}^{92}_{36}\mathrm{Kr}$.

☐ MeV

(b) What fraction of the initial rest energy of the system is transformed to other forms?

☐ %

2. –/0.333 points

For the fusion reaction shown below, find the amount of energy (Q) released. ☐ MeV

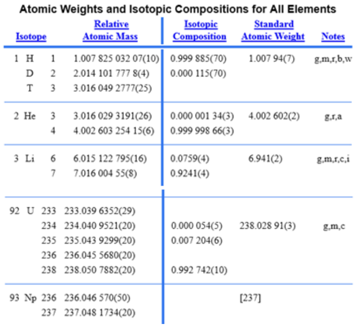
$${}^{1}_{1}H + {}^{2}_{1}H \longrightarrow {}^{3}_{2}He + \gamma$$

$$\text{Typical reaction :}$$
$$(\text{Reactants}) \rightarrow (\text{Products}) + \text{excess energy}$$
$$\text{excess energy} = \begin{cases} \text{kinetic energy (eg. neutron production)} \\ \text{photon energy} \end{cases}$$

Assume that any available mass can be converted to energy according to ***E=mc²*.**

$$1\ \text{u} = 1.660539 \times 10^{-27}\ \text{kg}$$
$$\text{E}_\text{u} = m_u c^2 = 1.660539 \times 10^{-27}\ \text{kg} \cdot \left(2.99792 \times 10^8\ \text{m/s}\right)^2$$
$$= 931.494\ \text{MeV}$$

Need table of atomic mass numbers:
http://www.nist.gov/pml/data/comp.cfm



Atomic Weights and Isotopic Compositions for All Elements

Isotope			Relative Atomic Mass	Isotopic Composition	Standard Atomic Weight	Notes
1	H	1	1.007 825 032 07(10)	0.999 885(70)	1.007 94(7)	g,m,r,b,w
	D	2	2.014 101 777 8(4)	0.000 115(70)		
	T	3	3.016 049 2777(25)			
2	He	3	3.016 029 3191(26)	0.000 001 34(3)	4.002 602(2)	g,r,a
		4	4.002 603 254 15(6)	0.999 998 66(3)		
3	Li	6	6.015 122 795(16)	0.0759(4)	6.941(2)	g,m,r,c,i
		7	7.016 004 55(8)	0.9241(4)		
92	U	233	233.039 6352(29)			
		234	234.040 9521(20)	0.000 054(5)	238.028 91(3)	g,m,c
		235	235.043 9299(20)	0.007 204(6)		
		236	236.045 5680(20)			
		238	238.050 7882(20)	0.992 742(10)		
93	Np	236	236.046 570(50)		[237]	
		237	237.048 1734(20)			

Neutron 1.008655 u

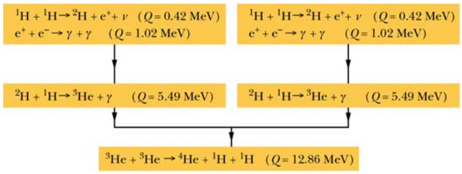
Example:

$${}^1_1\text{H} + {}^2_1\text{H} \rightarrow {}^3_2\text{He} + \gamma$$
$$\text{Energy available to } \gamma \text{ ray :}$$
$$\left[m\left({}^1_1\text{H}\right) + m\left({}^2_1\text{H}\right) - m\left({}^3_2\text{He}\right)\right]c^2 = \left[1.007825 + 2.014102 - 3.016029\right] \cdot 931.494\,\text{MeV}$$
$$= 0.005878 \cdot 931.494\,\text{MeV} = 5.475\ \text{MeV}$$

In principle, nuclear energy is available in both fission and fusion reactions.

Fusion reactions

Summary of reactions in the sun:



$^1H + {}^1H \rightarrow {}^2H + e^+ + \nu \quad (Q = 0.42\ \text{MeV})$
$e^+ + e^- \rightarrow \gamma + \gamma \quad (Q = 1.02\ \text{MeV})$

$^1H + {}^1H \rightarrow {}^2H + e^+ + \nu \quad (Q = 0.42\ \text{MeV})$
$e^+ + e^- \rightarrow \gamma + \gamma \quad (Q = 1.02\ \text{MeV})$

$^2H + {}^1H \rightarrow {}^3He + \gamma \quad (Q = 5.49\ \text{MeV})$

$^2H + {}^1H \rightarrow {}^3He + \gamma \quad (Q = 5.49\ \text{MeV})$

$^3He + {}^3He \rightarrow {}^4He + {}^1H + {}^1H \quad (Q = 12.86\ \text{MeV})$

Total energy release for each event: 26.7 MeV

This process has been occurring for ≈ 5 x 10^9 years and is expected to last for 10^9 more years

Fusion reactions which might be possible on earth:

$^2_1H + {}^2_1H \rightarrow {}^3_2He + n \quad (Q=3.27\ \text{MeV})$

$^2_1H + {}^2_1H \rightarrow {}^3_2He + {}^1_1H \quad (Q=4.03\ \text{MeV})$

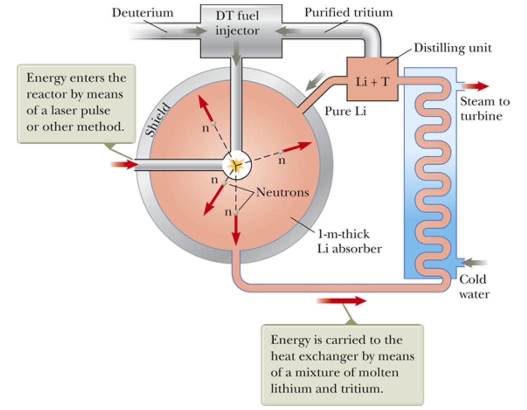
$^2_1H + {}^3_1H \rightarrow {}^4_2He + n \quad (Q=17.59\ \text{MeV})$

$n + {}^6_3Li \rightarrow {}^4_2He + {}^3_1H \quad (Q=4.78\ \text{MeV})$

Technological challenge: How to control the energetic reactants to effect net energy gain???

Magnetic confinement – "tokamak" design

Laser confinement – high powered lasers focused on fuel put into solid form



Energy enters the reactor by means of a laser pulse or other method.

Energy is carried to the heat exchanger by means of a mixture of molten lithium and tritium.

	Advantages	Disadvantages
Fission	Technology has been demonstrated	Nuclear waste
Fusion	Less dangerous nuclear waste	Technology has not yet been demonstrated

Nuclear power plant in France (photo from textbook)

Fission: Some history –

1932 James Chadwick (England) discovered neutron

Enrico Fermi (Italy) discovered that neutrons could be absorbed by nuclei to form new elements

Lise Meitner, Otto Hahn, Fritz Strassmann, Otto Frisch (Germany) discovered fission of U

Example:

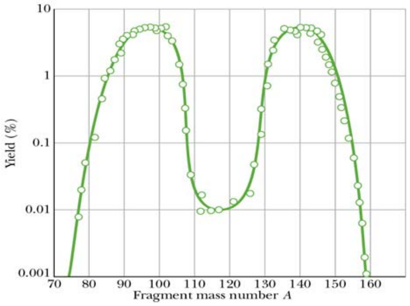
$$n+{}^{235}_{92}U\rightarrow{}^{236}_{92}U\rightarrow{}^{140}_{54}Xe+{}^{94}_{38}Sr+2n$$

$$\begin{array}{ccccccccc} {}^{140}_{54}Xe & \rightarrow & {}^{140}_{55}Cs & \rightarrow & {}^{140}_{56}Ba & \rightarrow & {}^{140}_{57}La & \rightarrow & {}^{140}_{58}Ce \\ (14\text{s}) & & (64\text{s}) & & (13\text{d}) & & (40\text{h}) & & (\text{stable}) \end{array}$$

$$\begin{array}{ccccc} {}^{94}_{38}Sr & \rightarrow & {}^{94}_{39}Y & \rightarrow & {}^{94}_{40}Zr \\ (75\text{s}) & & (19\text{min}) & & (\text{stable}) \end{array}$$

$Q \approx 200$ MeV

Other decay products for $n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U$



Mechanism for power plant

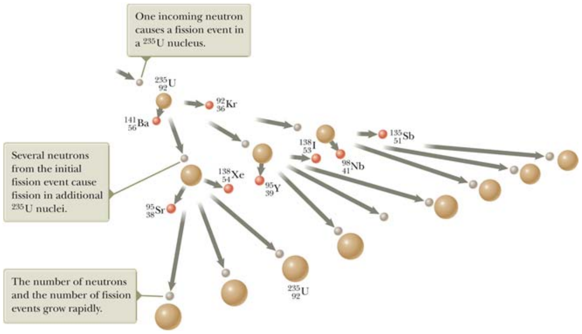
Heat → mechanical energy → generator → electricity

Heat sources:

Chemical burning: oxygen + coal, oil, etc.

Nuclear burning: $n + {}^{235}_{92}U$

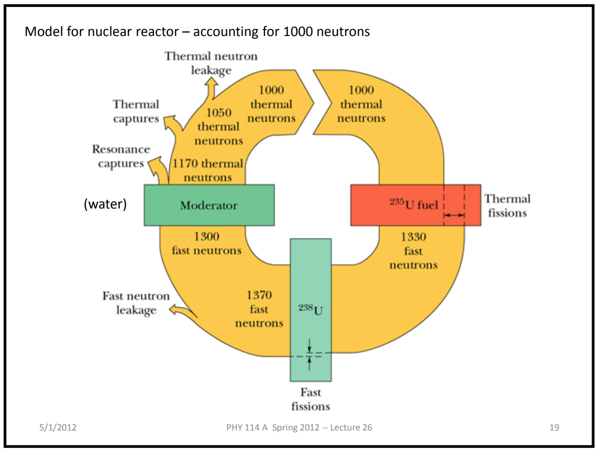
neutrons generated in the reaction are also used to fuel the reaction



One incoming neutron causes a fission event in a ^{235}U nucleus.

Several neutrons from the initial fission event cause fission in additional ^{235}U nuclei.

The number of neutrons and the number of fission events grow rapidly.



Model for nuclear reactor – accounting for 1000 neutrons

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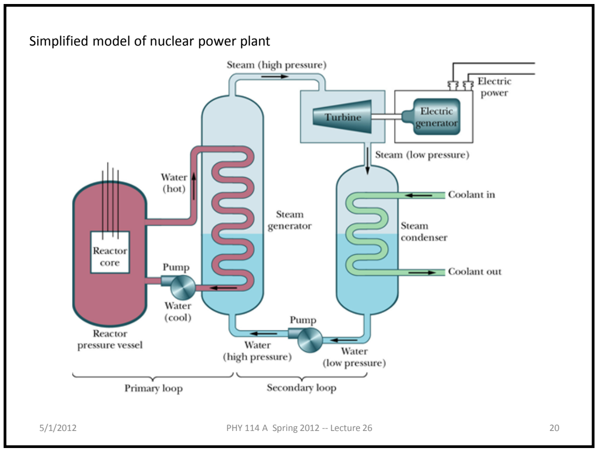

Simplified model of nuclear power plant

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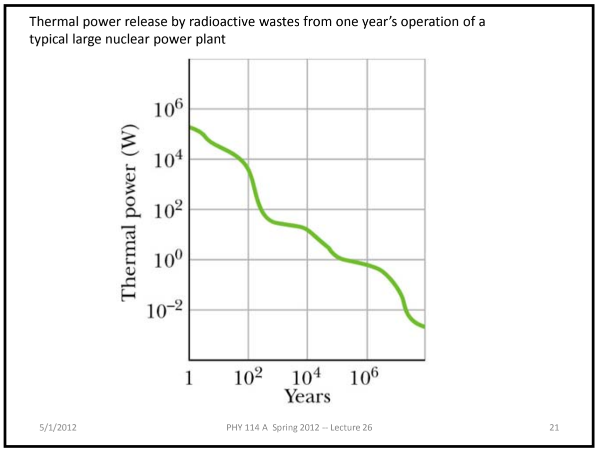

Thermal power release by radioactive wastes from one year's operation of a typical large nuclear power plant

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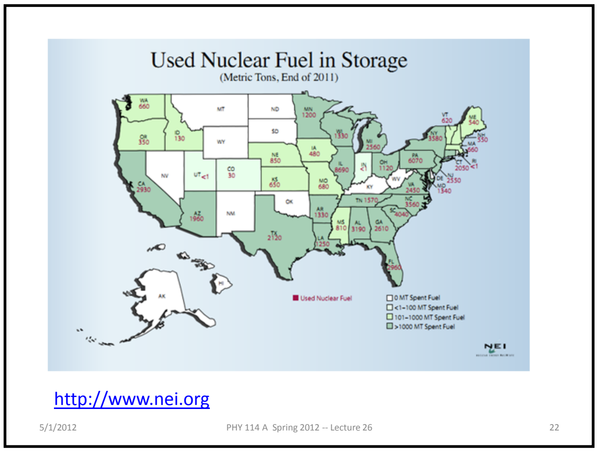
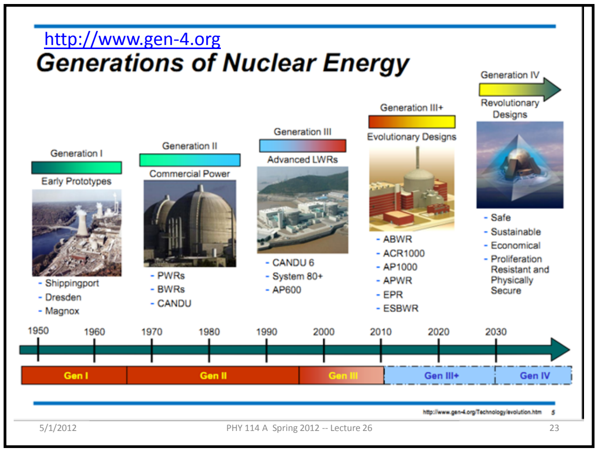


Used Nuclear Fuel in Storage

(Metric Tons, End of 2011)

http://www.nei.org



http://www.gen-4.org

Generations of Nuclear Energy

Generation I
Early Prototypes
- Shippingport
- Dresden
- Magnox

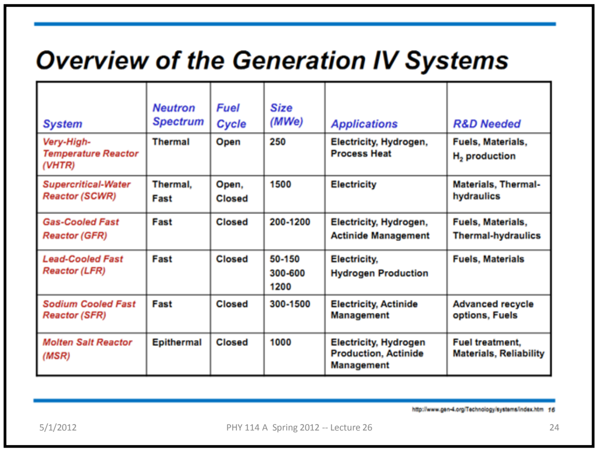
Generation II
Commercial Power
- PWRs
- BWRs
- CANDU

Generation III
Advanced LWRs
- CANDU 6
- System 80+
- AP600

Generation III+
Evolutionary Designs
- ABWR
- ACR1000
- AP1000
- APWR
- EPR
- ESBWR

Generation IV
Revolutionary Designs
- Safe
- Sustainable
- Economical
- Proliferation Resistant and Physically Secure

http://www.gen-4.org/Technology/evolution.htm 5



Overview of the Generation IV Systems

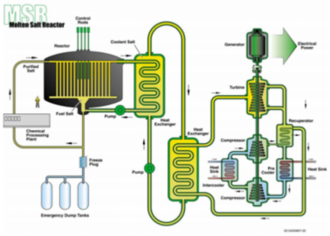
System	Neutron Spectrum	Fuel Cycle	Size (MWe)	Applications	R&D Needed
Very-High-Temperature Reactor (VHTR)	Thermal	Open	250	Electricity, Hydrogen, Process Heat	Fuels, Materials, H_2 production
Supercritical-Water Reactor (SCWR)	Thermal, Fast	Open, Closed	1500	Electricity	Materials, Thermal-hydraulics
Gas-Cooled Fast Reactor (GFR)	Fast	Closed	200-1200	Electricity, Hydrogen, Actinide Management	Fuels, Materials, Thermal-hydraulics
Lead-Cooled Fast Reactor (LFR)	Fast	Closed	50-150 300-600 1200	Electricity, Hydrogen Production	Fuels, Materials
Sodium Cooled Fast Reactor (SFR)	Fast	Closed	300-1500	Electricity, Actinide Management	Advanced recycle options, Fuels
Molten Salt Reactor (MSR)	Epithermal	Closed	1000	Electricity, Hydrogen Production, Actinide Management	Fuel treatment, Materials, Reliability

http://www.gen-4.org/Technology/systems/index.htm 16

Molten Salt Reactor (MSR)

Characteristics
- Fuel is liquid fluorides of U and Pu with Li, Be, Na and other fluorides
- 700–800C outlet temperature
- 1000 MWe
- Low pressure (<0.5 MPa)

Benefits
- Waste minimization
- Avoids fuel development
- Proliferation resistance through low fissile material inventory



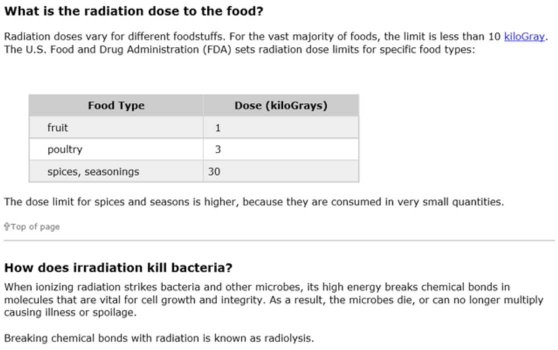
http://www.gen-4.org/Technology/systems/index.htm 15

Other uses of nuclear radiation
- Food irradiation:

http://www.epa.gov/rpdweb00/sources/food_irrad.html

Food irradiation is a technology for controlling spoilage and eliminating food-borne pathogens, such as salmonella. The result is similar to conventional pasteurization and is often called "cold pasteurization" or "irradiation pasteurization." Like pasteurization, irradiation kills bacteria and other pathogens, that could otherwise result in spoilage or food poisoning. The fundamental difference between the two methods is the source of the energy they rely on to destroy the microbes. While conventional pasteurization relies on heat, irradiation relies on the energy of ionizing radiation. The FDA emphasizes that no preservation method is a substitute for safe food handling procedures.

http://www.epa.gov/rpdweb00/sources/food_irrad.html



What is the radiation dose to the food?

Radiation doses vary for different foodstuffs. For the vast majority of foods, the limit is less than 10 kiloGray. The U.S. Food and Drug Administration (FDA) sets radiation dose limits for specific food types:

Food Type	Dose (kiloGrays)
fruit	1
poultry	3
spices, seasonings	30

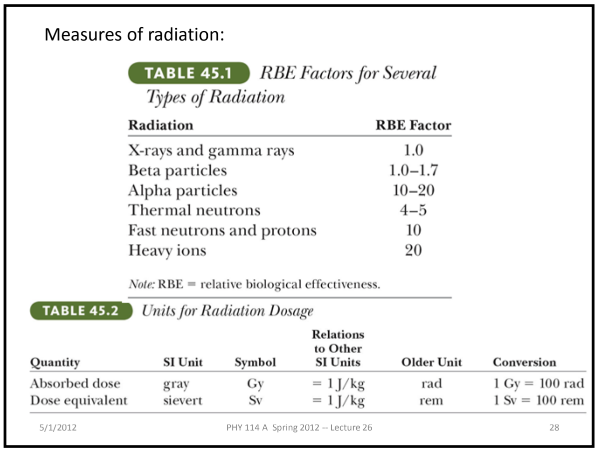
The dose limit for spices and seasons is higher, because they are consumed in very small quantities.

Top of page

How does irradiation kill bacteria?

When ionizing radiation strikes bacteria and other microbes, its high energy breaks chemical bonds in molecules that are vital for cell growth and integrity. As a result, the microbes die, or can no longer multiply causing illness or spoilage.

Breaking chemical bonds with radiation is known as radiolysis.



Measures of radiation:

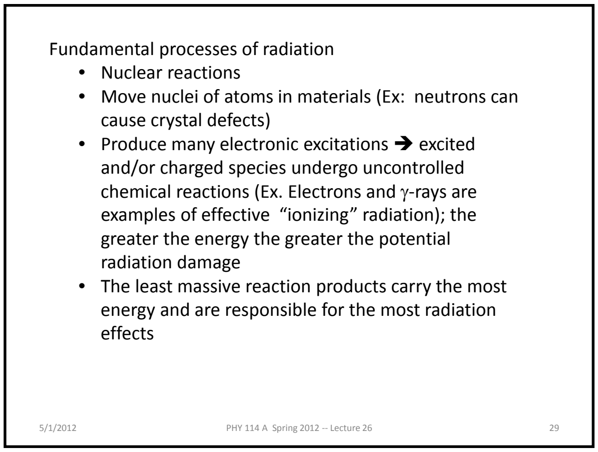
TABLE 45.1 *RBE Factors for Several Types of Radiation*

Radiation	RBE Factor
X-rays and gamma rays	1.0
Beta particles	1.0–1.7
Alpha particles	10–20
Thermal neutrons	4–5
Fast neutrons and protons	10
Heavy ions	20

Note: RBE = relative biological effectiveness.

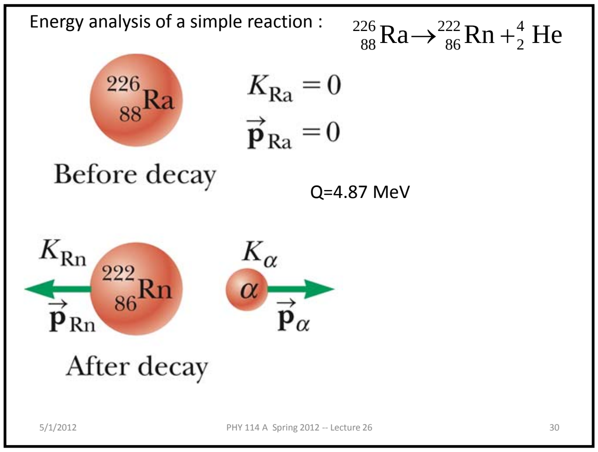
TABLE 45.2 *Units for Radiation Dosage*

Quantity	SI Unit	Symbol	Relations to Other SI Units	Older Unit	Conversion
Absorbed dose	gray	Gy	= 1 J/kg	rad	1 Gy = 100 rad
Dose equivalent	sievert	Sv	= 1 J/kg	rem	1 Sv = 100 rem



Fundamental processes of radiation

- Nuclear reactions
- Move nuclei of atoms in materials (Ex: neutrons can cause crystal defects)
- Produce many electronic excitations ➔ excited and/or charged species undergo uncontrolled chemical reactions (Ex. Electrons and γ-rays are examples of effective "ionizing" radiation); the greater the energy the greater the potential radiation damage
- The least massive reaction products carry the most energy and are responsible for the most radiation effects



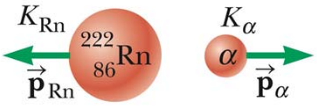
Energy analysis of a simple reaction : $^{226}_{88}\text{Ra}\rightarrow{}^{222}_{86}\text{Rn}+{}^{4}_{2}\text{He}$

$K_{\text{Ra}}=0$

$\vec{\mathbf{p}}_{\text{Ra}}=0$

Q=4.87 MeV

Energy analysis of a simple reaction : $^{226}_{88}\mathrm{Ra} \rightarrow ^{222}_{86}\mathrm{Rn} + ^{4}_{2}\mathrm{He}$



Q=4.87 MeV

$$\mathbf{p}_{Rn} = -\mathbf{p}_{He} \equiv \mathbf{p}$$

$$Q = \frac{p_{Rn}{}^2}{2m_{Rn}} + \frac{p_{He}{}^2}{2m_{He}} \approx \frac{p^2}{2m_u}\left(\frac{1}{222} + \frac{1}{4}\right)$$

$$E_{He} = \frac{p_{He}{}^2}{2m_{He}} = \frac{1/4}{1/222 + 1/4} Q = 0.98 \cdot Q = 4.8\mathrm{MeV}$$

Other uses of nuclear radiation

- Carbon dating

Living organisms have a ratio of ^{14}C / ^{12}C of 1.3x10^{-12} reflecting normal atmospheric processes. When an organism dies, the ratio is reduced due to the 5730 yr half-life of ^{14}C.

Example from your textbook: A piece of charcoal containing 25 g of carbon is found to have an activity of 4.167 decays/s. How long ago did the tree live that produced this charcoal?

Decay rate when tree was alive for 25 g of C:

$$\left|\frac{dN}{dt}\right|_0 = \lambda N_0 \quad \lambda = \frac{\ln 2}{5730\ \mathrm{yr} \cdot 3.1556 \times 10^7\ \mathrm{s/yr}} = 3.83 \times 10^{-12}/\mathrm{s}$$

$$N_0 = \frac{25}{12} \cdot 6.022 \times 10^{23} \cdot 1.3 \times 10^{-12} = 1.631 \times 10^{12} \quad \lambda \mathrm{N}_0 = 6.25\ \mathrm{decays/s}$$

Other uses of nuclear radiation

- Carbon dating -- continued

Decay rate when tree was alive for 25 g of C:

$$\left|\frac{dN}{dt}\right|_0 = \lambda N_0 \quad \lambda = \frac{\ln 2}{5730\ \mathrm{yr} \cdot 3.1556 \times 10^7\ \mathrm{s/yr}} = 3.83 \times 10^{-12}/\mathrm{s}$$

$$N_0 = \frac{25}{12} \cdot 6.022 \times 10^{23} \cdot 1.3 \times 10^{-12} = 1.631 \times 10^{12} \quad \lambda \mathrm{N}_0 = 6.25\ \mathrm{decays/s}$$

$$\text{Current decay rate}: \left|\frac{dN}{dt}\right| = \lambda N_0\, e^{-\lambda\lambda} = 4.1667\mathrm{decays/s}$$

$$\frac{\left|\frac{dN}{dt}\right|_0}{\left|\frac{dN}{dt}\right|} = e^{\lambda t} \quad \Rightarrow \quad t = \frac{1}{3.83 \times 10^{-12}/\mathrm{s}} \ln\left(\frac{6.25}{4.17}\right) = 1.06 \times 10^{11} s = 3400 yr$$