1. The two types of nuclear reactions are radioactive decay and nuclear bombardment reactions.

Radioactive decay: $${}^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}b$$

Nuclear bombardment: $${}^{14}_{7}N + {}^{4}_{2}He \rightarrow {}^{17}_{8}O + {}^{1}_{1}H$$

4.

1.	alpha emission	alpha emission usually occurs with the heaviest unstable nuclei
2.	beta emission	beta emission is usually observed for nuclei that have a neutron to proton ratio N/Z which is larger than those nuclei within the band of stability.
3.	positron emission	positron emission is usually observed for nuclei that have a neutron to proton ratio N/Z which is smaller than those nuclei within the band of stability.
4.	electron capture	electron capture is usually observed for nuclei that have a neutron to proton ratio N/Z which is smaller than those nuclei within the band of stability.
5.	gamma emission	gamma emission occurs when a nucleus is formed in an excited state.
6.	spontaneous fission	spontaneous fission usually occurs with the heaviest unstable nuclei.

11. This would require three half-lives. After the first half life, ½ of the sample remains. After the second half-life, ¼ of the sample remains and after the third half-life **c** of the sample remains. Therefore, 3 x 30.2 y = 90.6 y is required.

17. This is a fusion reaction where the total binding energy in the product nuclei is greater than the total binding energy in the reactant nuclei. Fe-56 is near the maximum of the binding energy per nucleon plot, so as long as the product is lighter than Fe-56 it will be more stable than the two reactants. Therefore, energy is released in the process.

19. a. The fraction of material remaining after n half-lives is $(½)^{n}$. Therefore, after 10 half lives, the fraction of material remaining is $(½)^{10} = 0.00098 = 0.098\%$.

    b. If there is initially a sizable quantity, 0.098% may still be a significant quantity.

21. The ^{23}Na atom has a mass which is smaller than the sum of the masses of its particles. This mass

defect as it is called is a reflection of the binding energy of the nucleus.

25. Alpha particles, which are positively charged, are deflected by the nuclei in the matter which they encounter. Gamma radiation on the other hand is high energy electromagnetic radiation, which, like X-rays, passes through many materials easily.

27. Irradiation with gamma rays does not induce changes in the nucleus of the atoms in the sample. Therefore, if there are no unstable atoms in the meat before irradiation, there will be none after. The addition of radioactive elements to the meat or, under the right conditions, nuclear bombardment will make the meat radioactive.

29. $^{87}_{37}Rb \rightarrow \, ^{87}_{38}Sr + \, ^{o}_{-1}b$

31. $^{232}_{90}Th \rightarrow \, ^{228}_{88}Ra + \, ^{4}_{2}He$

33. $^{18}_{9}F \rightarrow \, ^{18}_{8}O + \, ^{0}_{1}b^{+}$

35. $^{210}_{84}Po \rightarrow \, ^{206}_{82}Pb + \, ^{4}_{2}He$

37. a. $^{122}_{51}Sb$, $^{136}_{54}Xe$ Neither has a magic number of protons. The Sb isotope has 122 − 51 = 71 neutrons and the Xe isotope has 136 − 54 = 82 (a magic number) so the Xe is the stable isotope and the Sb is radioactive.

b. $^{204}_{82}Pb$, $^{204}_{85}At$ Pb has a magic number of protons (82), while At does not. In addition, At has a Z greater than 83 and is therefore not stable.

c. $^{87}_{37}Rb$, $^{80}_{37}Rb$ ^{87}Rb has 87 − 37 = 50 neutrons. This is a magic number, so ^{87}Rb is the stable isotope.

39. a. $^{228}_{92}U$ has a Z greater than 83 and is likely to undergo decay by alpha emission, which, in fact, it does.

b. ${}^{8}_{5}B$ has a low neutron to proton ratio (3:5) and is therefore expected to undergo positron emission or electron capture. ${}^{8}_{5}B$ actually undergoes positron emission and results in the production of 2 alpha particles.

c. ${}^{68}_{29}Cu$ N/Z = 1.34, so β emission is expected and observed.

41. Alpha emission decreases the mass number by 4 while beat emission leaves the mass number unchanged. The naturally occurring decay series begin with ^{238}U, ^{235}U and ^{232}Th and the synthetic decay series begins with ^{241}Pu.

^{219}Rn has a mass number 16 less than ^{235}U, corresponding to 4 α particles. It therefore belongs to the ^{235}U decay series.

^{220}Rn has a mass number 12 less than ^{232}Th, corresponding to 3 α particles. It therefore belongs to the ^{232}Th decay series.

43. a. ${}^{26}_{12}Mg\ (d\,,a\ )\ {}^{24}_{11}Na$

b. ${}^{16}_{8}O\ (n\,,p\ )\ {}^{16}_{7}N$

45. a. ${}^{27}_{13}Al + {}^{2}_{1}H \rightarrow {}^{25}_{12}Mg + {}^{4}_{2}He$

b. ${}^{10}_{5}B + {}^{4}_{2}He \rightarrow {}^{13}_{6}C + {}^{1}_{1}H$

47.
$$\frac{12.6\ \text{MeV}}{\text{proton}} \times \frac{6.022 \times 10^{23}\ \text{protons}}{1\ \text{mol}} \times \frac{1000\ \text{eV}}{1\ \text{MeV}}$$

$$\times \frac{1.602 \times 10^{-19}\ \text{J}}{1\ \text{eV}} \times \frac{1\ \text{kJ}}{1000\ \text{J}} = 1.22 \times 10^{9}\ \frac{\text{kJ}}{\text{mol}}$$

49. a. $^{6}_{3}Li + ^{1}_{0}n \rightarrow ^{4}_{2}He + ^{3}_{1}H$

b. $^{232}_{90}Th\ (a\ ,\ n)\ ^{235}_{92}U$

51. $^{A}_{Z}X + ^{4}_{2}He \rightarrow ^{242}_{96}Cm + ^{1}_{0}n$, therefore, $^{A}_{Z}X = ^{239}_{94}Pu$

53. $0.250 \text{ x } 10^{-3} \text{ g H-3 x } \frac{1 \text{ mol}}{3.02 \text{ g}} \text{ x } \frac{6.022 \text{ x } 10^{23} \text{ nuclei}}{1 \text{ mol}} = 4.9\underline{8}5 \text{ x } 10^{19} \text{ nuclei}$

$$k = \frac{8.94 \text{ x } 10^{10}\ \frac{\text{nuclei}}{\text{s}}}{4.9\underline{8}5 \text{ x } 10^{19} \text{ nuclei}} = 1.79 \text{ x } 10^{-9} \text{ s}^{-1}$$

55. $0.48 \text{ x } 10^{-3} \text{ g S-35 x } \frac{1 \text{ mol}}{34.969031 \text{ g}} \text{ x } \frac{6.022 \text{ x } 10^{23} \text{ nuclei}}{1 \text{ mol}} = 8.3 \text{ x } 10^{18} \text{ nuclei}$

$$20.4 \text{ Ci x } \frac{3.700 \text{ x } 10^{10}\ \frac{\text{disintegrations}}{\text{s}}}{1 \text{ Ci}} = 7.5 \text{ x } 10^{11}\ \frac{\text{disintegrations}}{\text{s}}$$

$$k = \frac{7.5 \text{ x } 10^{11}\ \frac{\text{nuclei}}{\text{s}}}{8.3 \text{ x } 10^{18} \text{ nuclei}} = 9.0 \text{ x } 10^{-8} \text{ s}^{-1}$$

57. $t_{1/2} = \frac{\ln 2}{k} = \frac{0.693}{k}$

$$t_{1/2} = \frac{0.693}{1.7 \text{ x } 10^{-21} \text{ s}^{-1}} = 4.1 \text{ x } 10^{20} \text{ s}$$

$$t_{1/2} = 4.1 \text{ x } 10^{20} \text{ s x } \frac{1 \text{ h}}{3600 \text{ s}} \text{ x } \frac{1 \text{ d}}{24 \text{ h}} \text{ x } \frac{1 \text{ y}}{365.25 \text{ d}} = 1.3 \text{ x } 10^{13} \text{ y}$$

59. $t_{1/2} = 5.73 \times 10^3 \text{ y} \times \dfrac{365.25 \text{ d}}{1 \text{ y}} \times \dfrac{24 \text{ h}}{1 \text{ d}} \times \dfrac{3600 \text{ s}}{1 \text{ h}} = 1.81 \times 10^{11} \text{ s}$

$$k = \frac{0.693}{t_{1/2}} \quad \frac{0.693}{1.81 \times 10^{11} \text{ s}} = 3.83 \times 10^{-12} \text{ s}^{-1}$$

61. $k = \dfrac{0.693}{2.69 \text{ d}} \times \dfrac{1 \text{ d}}{24 \text{ h}} \times \dfrac{1 \text{ h}}{3600 \text{ s}} = 2.98 \times 10^{-6} \text{ s}^{-1}$

$$0.86 \times 10^{-3} \text{ g Au-198} \times \frac{1 \text{ mol}}{197.968 \text{ g}} \times \frac{6.022 \times 10^{23} \text{ nuclei}}{1 \text{ mol}} = 2.6 \times 10^{18} \text{ nuclei}$$

$$\text{rate} = k \times N_t = 2.98 \times 10^{-6} \text{ s}^{-1} \times 2.6 \times 10^{18} \text{ nuclei} = 7.8 \times 10^{12} \frac{\text{nuclei}}{\text{s}}$$

$$\text{activity} = 7.8 \times 10^{12} \frac{\text{nuclei}}{\text{s}} \times \frac{1 \text{ Ci}}{3.700 \times 10^{10} \frac{\text{nuclei}}{\text{s}}} = 2.1 \times 10^2 \text{ Ci}$$

63. $k = \dfrac{0.693}{14.3 \text{ d}} \times \dfrac{1 \text{ d}}{24 \text{ h}} \times \dfrac{1 \text{ h}}{3600 \text{ s}} = 5.61 \times 10^{-7} \text{ s}^{-1}$

$$N_t = \frac{\text{rate}}{k} = \frac{6.0 \times 10^{12} \frac{\text{nuclei}}{\text{s}}}{5.61 \times 10^{-7} \text{ s}^{-1}} = 1.1 \times 10^{19} \text{ nuclei}$$

$$1.1 \times 10^{19} \text{ nuclei} \times \frac{31.9739 \text{ g}}{6.022 \times 10^{23} \text{ nuclei}} = 5.8 \times 10^{-4} \text{ g} = 0.58 \text{ mg P-32}$$

65. $k = \dfrac{0.693}{t_{1/2}} = \dfrac{0.693}{15.0 \text{ h}} = 4.62 \times 10^{-2} \text{ h}^{-1}$

$$\ln \frac{N_t}{N_0} = -kt = -4.62 \times 10^{-2} \text{ h}^{-1} \times 12.0 \text{ h} = -0.554$$

$\dfrac{N_t}{N_0} = e^{-0.554} = 0.574$ After 12.0 hours, 57.4% of the isotope remains.

0.574 x 6.0 μg = 3.4 μg

67. If 28.0 % decays, 72.0 % remains, so $\frac{N_t}{N_0} = 0.720$

$$\ln 0.720 = -k \times 1.97\ s = -0.328$$

$$k = \frac{-0.328}{-1.97\ s} = 0.166\ s^{-1}$$

$$t_{1/2} = \frac{\ln 2}{k} = \frac{0.693}{0.166\ s^{-1}} = 4.17\ s$$

69. $\ln \frac{107}{125} = -k \times 10.0\ d = -0.155$

$$k = \frac{-0.155}{-10.0\ d} = 1.55 \times 10^{-2}\ d^{-1}$$

$$t_{1/2} = \frac{\ln 2}{k} = \frac{0.693}{1.55 \times 10^{-2}\ d^{-1}} = 44.7\ d$$

71. $k = \frac{0.693}{t_{1/2}} = \frac{0.693}{5730\ y} = 1.21 \times 10^{-4}\ y^{-1}$

$$\ln \frac{8.1}{15.3} = -1.21 \times 10^{-4}\ y^{-1} \times t = -0.64$$

$$t = \frac{-0.64}{-1.21 \times 10^{-4}\ y^{-1}} = 5.3 \times 10^{3}\ y$$

73. $\ln \frac{N_t}{N_0} = -1.21 \times 10^{-4}\ y^{-1} \times 9.0 \times 10^{3}\ y = -1.\underline{0}8$

$$\frac{N_t}{N_0} = e^{-1.\underline{0}8} = 0.34$$

$$N_t = 0.34 \times N_0 = 0.34 \times 15.3\ \frac{\text{disintegrations}}{\text{g}\cdot\text{min}} = 5.2\ \frac{\text{disintegrations}}{\text{g}\cdot\text{min}}$$

75. $E = mc^2$

$$m = \frac{393{,}500 \text{ J}}{(2.998 \times 10^{8} \frac{\text{m}}{\text{s}})^2} = 4.378 \times 10^{-12} \text{ kg}$$

Remember, $1 \text{ J} = 1 \frac{\text{kg} \cdot \text{m}^2}{\text{s}^2}$

77. $${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n$$

mass of reactants = 2.01400 amu + 3.01605 amu = 5.03005 amu

mass of products = 4.00260 amu + 1.008665 amu = $5.0112\underline{6}5$ amu

Δ mass = 5.03005 amu − $5.0112\underline{6}5$ amu = $0.0187\underline{8}5$ amu

$$\Delta m = 0.0187\underline{8}5 \text{ amu} \times \frac{1 \text{ g}}{6.0221367 \times 10^{23}} \times \frac{1 \text{ kg}}{1000 \text{ g}} = 3.119 \times 10^{-29} \text{ kg}$$

$$E = 3.119 \times 10^{-29} \text{ kg} \times (2.998 \times 10^{8} \frac{\text{m}}{\text{s}})^2 = 2.803 \times 10^{-12} \text{ J} \quad \text{(per deuteron)}$$

$$E = 2.803 \times 10^{-12} \frac{\text{J}}{\text{deuteron}} \times \frac{6.0221367 \times 10^{23} \text{ deuterons}}{\text{mol}} = 1.688 \times 10^{12} \frac{\text{J}}{\text{mol}}$$

$$E = \frac{2.803 \times 10^{-12} \text{ J}}{\text{deuteron}} \times \frac{1 \text{ eV}}{1.602 \times 10^{-19} \text{ J}} \times \frac{1 \text{ MeV}}{10^{6} \text{ eV}} = 17.50 \text{ MeV per deuteron}$$

79. ${}^{6}_{3}Li$ consists of 3 protons and 3 neutrons and has a mass of 6.01512 amu. The mass of 3 protons and 3 neutrons is 3(1.00728) + 3(1.008665) amu = 6.047835 amu.

The mass defect is 6.047835 amu −6.01512 amu = $0.0327\underline{1}5$ amu

$$0.0327\underline{1}5 \text{ amu} \times \frac{1 \text{ kg}}{6.02214 \times 10^{26} \text{ amu}} = 5.432 \times 10^{-29} \text{ kg}$$

$$E = 5.432 \times 10^{-29} \text{ kg} \times (2.998 \times 10^{8} \frac{\text{m}}{\text{s}})^2 \times \frac{1 \text{ MeV}}{1.602 \times 10^{-13} \text{ J}} = 30.48 \text{ MeV (per nucleus)}$$

$$E = \frac{30.48\ \text{MeV}}{6\ \text{nucleons}} = 5.080\ \frac{\text{MeV}}{\text{nucleon}}$$

81.

^{20}Na has 11 protons and 9 neutrons. N/Z = 0.81.	positron emission or electron capture will increase N/Z and are likely modes of decay. Positron emission is actually observed.
^{26}Na has 11 protons and 15 neutrons. N/Z = 1.36.	β emission will decrease N/Z and is a likely mode of decay and is observed.

83. Each α-emission decreases the atomic number by 2 and mass number by 4. Each β emission increases the atomic number by 1 and leaves the mass number unchanged.

The difference in mass number between ^{235}U and ^{207}Pb is 28, corresponding to 7 α emissions.

The difference in atomic number between $_{92}$U and $_{82}$Pb is 10. The 7 α emissions decreases Z by 14, so 4 β emissions are also required to account for the difference of 10 in mass number.

85. $^{209}_{83}Bi + {}^{4}_{2}He \rightarrow {}^{211}_{85}At + 2\,{}^{1}_{0}n$

87. $^{238}_{92}U + {}^{12}_{6}C \rightarrow {}^{246}_{98}Cf + 4\,{}^{1}_{0}n$

89. $k = \frac{0.693}{t_{1/2}} = \frac{0.693}{12.3\ \text{y}} = 5.63 \times 10^{-2}\ \text{y}^{-1}$

$$\ln 0.70 = -5.63 \times 10^{-2}\ \text{y}^{-1} \times t = -0.3\underline{5}6$$

$$t = \frac{-0.3\underline{5}6}{-5.63 \times 10^{-2}\ \text{y}^{-1}} = 6.3\ \text{y}$$

91. When the positron and electron are annihilated, the final mass is 0. Therefore Δm is equal to the sum of the masses of the electron and the positron.

$\Delta m = 0.000549\ \text{amu} + 0.000549\ \text{amu} - 0 = 0.001098\ \text{amu}$.

$$\Delta m = 0.001098\ \text{amu} \times \frac{1\ \text{g}}{6.0221367 \times 10^{23}} \times \frac{1\ \text{kg}}{1000\ \text{g}} = 1.823 \times 10^{-30}\ \text{kg}$$

$$\text{total E} = 1.823 \times 10^{-30}\ \text{kg} \times (2.998 \times 10^{8}\ \tfrac{\text{m}}{\text{s}})^{2} = 1.639 \times 10^{-13}\ \text{J}$$

$$\text{E (per } \gamma \text{ photon)} = \frac{1.639 \times 10^{-13}\ \text{J}}{2} = 8.193 \times 10^{-14}\ \text{J}$$

$$\lambda = \frac{hc}{E} = \frac{(6.626 \times 10^{-34}\ \text{J}\cdot\text{s})(2.998 \times 10^{8}\ \text{m}\cdot\text{s}^{-1})}{8.193 \times 10^{-14}\ \text{J}} = 2.425 \times 10^{-12}\ \text{m} = 2.425\ \text{pm}$$

93. $${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{136}_{53}I + {}^{96}_{39}Y + 4\,{}^{1}_{0}n$$

mass of reactants = 235.04392 + 1.008665 = 236.05258 amu

mass of products = 135.8401 + 95.8629 + 4 (1.008665) = 235.7377 amu

Δm = 0.3149 amu

$$\Delta m = 0.3149\ \text{amu} \times \frac{1\ \text{g}}{6.0221367 \times 10^{23}} \times \frac{1\ \text{kg}}{1000\ \text{g}} = 5.229 \times 10^{-28}\ \text{kg}$$

$$E = 5.229 \times 10^{-28}\ \text{kg} \times (2.998 \times 10^{8}\ \tfrac{\text{m}}{\text{s}})^{2} = 4.700 \times 10^{-11}\ \text{J} \quad \text{(per U-235)}$$

$$5.00\ \text{kg} \times \frac{1000\ \text{g}}{1\ \text{kg}} \times \frac{1\ \text{mol}}{235.04392} \times \frac{6.02214 \times 10^{23}\ \text{nuclei}}{1\ \text{mol}} = 1.28 \times 10^{25}\ \text{nuclei}$$

$$1.28 \times 10^{25}\ \text{nuclei} \times \frac{4.700 \times 10^{-11}\ \text{J}}{\text{nucleus}} = 6.01 \times 10^{14}\ \text{J}$$

$$5.00\ \text{kg C} \times \frac{1000\ \text{g}}{1\ \text{kg}} \times \frac{1\ \text{mol}}{12.011\ \text{g C}} \times \frac{-393{,}500\ \text{J}}{1\ \text{mol}} = -1.63 \times 10^{8}\ \text{J}$$

The energy available from the fission of 5.00 kg ^{235}U is about 3,690,000 times that from the combustion of 5.00 kg graphite.

95. a. $${}^{47}_{20}Ca \rightarrow {}^{47}_{21}Sc + {}^{0}_{-1}b$$

b. $$k = \frac{\ln 2}{t_{1/2}} = \frac{0.693147}{4.536\ \text{d}} = 0.1528\ \text{d}^{-1}$$

$$\ln \frac{10.0\ \mu g}{m} = -0.1528\ d^{-1} \times 2.0\ d = -0.31$$

$$\frac{10.0\ \mu g}{m} = e^{-0.31} = 0.73$$

$$m = \frac{10.0\ \mu g}{0.73} = 14\ \mu g$$

$$14\ \mu g\ {}^{47}Ca \times \frac{143.03\ \mu g\ {}^{47}CaSO_4}{46.9545\ \mu g\ {}^{47}Ca} = 43\ \mu g\ {}^{47}CaSO_4$$

97. a. $${}^{82}_{35}Br \rightarrow {}^{82}_{36}Kr + {}^{0}_{-1}e$$

$$2\ H\,{}^{82}Br \rightarrow H_2 + 2\ {}^{82}Kr$$

b. $$k = \frac{\ln 2}{t_{1/2}} = \frac{0.693147}{1.471\ d} = 0.4712\ d^{-1}$$

$$\ln \frac{n_t}{0.0150\ mol} = -0.4712\ d^{-1} \times 0.500\ d = -0.23\underline{5}6$$

$$\frac{n_t}{0.0150\ mol} = e^{-0.23\underline{5}6} = 0.790$$

n_t = (0.790)(0.0150 mol) = $0.011\underline{8}5$ mol HBr remains

and 0.0150 − $0.011\underline{8}5$ = $0.003\underline{1}5$ mol HBr decomposes

According to the balanced equation, each two moles of HBr that decomposes produce 1 mol H_2 and 2 mol Kr (or 3 total mol gas)

Total moles of gas in the flask = $0.011\underline{8}5$ mol + 3/2 ($0.003\underline{1}5$ mol) = $0.016\underline{5}7$ mol

$$P = \frac{nRT}{V} = \frac{(0.016\underline{5}7\ mol)(0.082058\ \frac{L\cdot atm}{mol\cdot K})(295\ K)}{1.00\ L} = 0.401\ atm$$