Chapter 68 NUCLEAR CHEMISTRY, Part 3

We now consider more of the math, and some of the aftermath, of radioactivity. For the math, we now turn to energy. Recall Chapter 66:

> “ Everything about nuclear change involves very large energies, and those energies can easily be millions of times greater than usual chemical energies. Instead of typical chemical reactions involving hundreds or thousands of kJ's, many nuclear processes will involve millions or billions of kJ's, even on a one-mole scale. The energies are simply outrageously high, and we will see more of this later. ”

Later is now.

68.1 Mass-energy

While we typically consider mass and energy to be completely different entities, they are actually part of each other. We very briefly touched on this back in Section 18.2.

> “ At a fundamental level, energy and mass are mutually interconnected, and this connection is called mass-energy equivalence. Energy has some amount of mass and mass has some amount of energy. The grand total of mass-energy stays the same across the universe; this constitutes the law of conservation of mass-energy. But energy has only a minute amount of mass, so you need to have a humongous amount of energy in order to have a measurable amount of mass. Humongous amounts of energy are involved in nuclear processes, and we will apply the mass-energy relationship to those in Chapter 68. On the other hand, chemical reactions, even explosions, do not involve such humongous amounts of energy; because of this, the mass of the energy involved in chemical reactions is ridiculously small and not significant. ”

OK, we're not just doing combustions anymore, we're doing nukes. Due to the magnitude of scale for the energies of nuclear processes, we must start taking into account the mass-energy relationship.

Fundamentally, mass is a property of energy and energy is a property of mass. The ratio of energy, E, to its associated mass, m, is equal to the speed of light squared.

$$\frac{E}{m} = c^2$$

Since $c = 3.00 \times 10^8$ m/s, and since it is squared here, then this ratio is extremely large. That's important to note. Thus, a small amount of mass is associated with a huge amount of energy, while a modest amount of energy has an extremely minute amount of mass. We don't normally take mass-energy equivalence into account in the normal everyday world because we don't normally deal with the magnitude of energies which are required in order for this to be significant. But we need this now because nuclear processes will put you in this range.

The above relationship is more commonly written as

$$E = mc^2$$

which is one of the most famous equations of the 20th century. Let's illustrate for a very modest sample size: consider a mass of 1.00 mg. Calculate the amount of energy which has 1.00 mg of mass. We'll need the mass in kg, 1.00×10^{-6} kg.

$$E = mc^2 = 1.00 \times 10^{-6}\ \text{kg} \times (3.00 \times 10^8\ \text{m/s})^2 = 9.00 \times 10^{10}\ \frac{\text{kg} \bullet \text{m}^2}{\text{s}^2}$$

The reason for converting mg to kg is contained within the definition of joule from Section 18.2.

$$\text{J} = \frac{\text{kg} \bullet \text{m}^2}{\text{s}^2}$$

We can use this to put the result into our more familiar unit of J's and kJ's.

$$9.00 \times 10^{10}\ \frac{\text{kg} \bullet \text{m}^2}{\text{s}^2} = 9.00 \times 10^{10}\ \text{J} = 9.00 \times 10^7\ \text{kJ}$$

This says that the energy equivalent of 1.00 mg of mass is 9.00×10^{10} J which is 90.0 million kJ which is 90.0 GJ. GJ? That's gigajoules, 10^9 J! That's huge, far in excess of anything we have previously considered. For a nuclear process which results in the release of 90.0 GJ of energy from the system to the surroundings, 1.00 mg mass is carried off by that energy. As always, mass remains conserved; since the energy carries off 1.00 mg, the combined masses of products are 1.00 mg less than the combined masses of reactants.

Compare this to all of our prior considerations for mass balance in a typical chemical reaction. For those cases, the combined masses of the reactants equaled the combined masses of the products, and we did not worry about the mass of the energy transferred. The reason for that is based on a very practical consideration: the mass of the energy involved would be immeasurably small. Let's do an illustration on this scale, using the combustion of C(*graph*).

$$C(graph) + O_2(g) \rightarrow CO_2(g) \qquad \Delta H° = -393.52 \text{ kJ}$$

This reaction releases 393.52 kJ for one mol C(*graph*) reacting with one mol $O_2(g)$. Now, calculate the mass of that energy release. Take the mass-energy equation

$$E = mc^2$$

and re-arrange for mass.

$$m = \frac{E}{c^2}$$

The energy released can be written as

$$393.52 \text{ kJ} = 393{,}520 \text{ J} = 393{,}520 \frac{\text{kg} \bullet \text{m}^2}{\text{s}^2}$$

and you can plug that in to find m.

$$m = \frac{393{,}520 \text{ kg} \bullet \text{m}^2/\text{s}^2}{(3.00 \times 10^8 \text{ m/s})^2} = 4.37 \times 10^{-12} \text{ kg} = 4.37 \times 10^{-9} \text{ g} = 4.37 \text{ ng}$$

This tells you that the mass carried by the energy into the surroundings for this combustion is an extremely minute 4.37 ng; we can also represent this as $\Delta m = -4.37$ ng. The total mass of reactants is 44.01 g and the mass of product is 44.01 g, and we are not able to measure a change of 4.37 ng out of that. This example is very representative of the scale of chemical reactions: the mass of the energy which is lost or gained by the system is far too small to make a measurable change in the total mass of products and reactants. Thus, for practical purposes, mass-energy equivalence need not be considered for chemical reactions.

Since mass-energy equivalence is now significant for nuclear processes, we can use it for calculating the energy of any decay or of any nuclear reaction. We cover the energies of decay now; we cover the energies of nuclear reactions in the next Chapter. For all cases, we calculate the difference in mass, Δm, between products and reactants; this is just another type of products-minus-reactants problem. That difference of mass is carried off by the energy, and we can determine the amount of that energy using the mass-energy relationship.

68.2 Mass-energy of decay

At this time, we'll cover the calculations for four of our six types of decay. I'm leaving out the calculation for spontaneous fission here, but we will cover this for induced fission in Chapter 69. I'm leaving out positron emission completely since those calculations are a bit different and we have enough to work with otherwise.

We start with α decay. Our first example in Section 66.2 was ^{238}U.

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}\alpha$$

We begin by finding Δm. We need some masses for one mole of each reagent. Again, these masses will be specific for the given isotope of the given element shown. We'll also need more decimal places since values for Δm can be quite a ways past the decimal. Here are some molar masses; note that ^4He is used for α.

$^{238}_{92}U$	→	$^{234}_{90}Th$	+	$^{4}_{2}He$
238.050787		234.043600		4.002603

Find Δm.

$$\Delta m = 234.043600\text{ g} + 4.002603\text{ g} - 238.050787\text{ g} = -0.004584\text{ g}$$

The negative sign of Δm means mass is lost. Now, does 4.584 mg sound like much of a loss? What about the energy corresponding to 4.584 mg?

$$E = mc^2 = 4.584 \times 10^{-6}\text{ kg} \times (3.00 \times 10^8\text{ m/s})^2 = 4.13 \times 10^{11}\text{ J} = 413\text{ GJ}$$

That is a huge amount of energy, and that is the energy for this α decay.

By the way, the E and m in $E = mc^2$ represent the energy released and the mass corresponding to that energy, expressed as positive numbers. We could instead write $\Delta E = (\Delta m)c^2$ and the Δ quantities would employ a sign (negative for a release), just as we had seen previously for ΔH, ΔS and ΔG in numerous prior Chapters dealing with thermodynamics. But nuclear chemistry commonly uses $E = mc^2$ with positive numbers, and we will follow that practice.

Also, by the way, all radioactive decays release energy and none require energy to occur. Since they release energy, they lose mass with that energy. As such, a daughter always has less mass than the parent, and Δm is always negative (even though it is entered as a positive m into $E = mc^2$).

OK, there was an element of subtlety involved in the above α decay: I used molar mass values for neutral atoms. Back in Section 66.1, I had written this decay in chemical terms, starting from uranium metal.

$$\text{U} \rightarrow \text{Th}^{2-} + \text{He}^{2+}$$

Under this scenario, we are not dealing with neutral Th nor with neutral He, but this does not matter when we add up the masses.

$$\begin{array}{rcl} \text{mass of Th}^{2-} & = & \text{mass of Th} + \text{mass of two e}^- \\ \text{mass of He}^{2+} & = & \text{mass of He} - \text{mass of two e}^- \\ \hline \text{mass of Th}^{2-} + \text{mass of He}^{2+} & = & \text{mass of Th} + \text{mass of He} \end{array}$$

The electron masses cancel out. For this reason, we can use the masses of neutral reactants and products for these calculations without keeping track of electron masses.

Let's do a beta negative decay.

$$^{3}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + {}^{0}_{-1}\beta$$

If we consider chemical charges starting with a neutral H atom (such as in H_2), then

$$\text{H} \rightarrow \text{He}^+ + \beta^-$$

but β^- is just an electron anyway. So, the mass of He^+ plus the mass of one e^- is the same as the mass of one neutral atom of He. Again, we just use the masses of the neutral atoms.

$^{3}_{1}\text{H}$	$\rightarrow$	$^{3}_{2}\text{He}$	+	$^{0}_{-1}\beta$
3.016049		3.016029		

From that, find the change in mass.

$$\Delta m = 3.016029\text{ g} - 3.016049\text{ g} = -0.000020\text{ g}$$

Calculate the energy of that mass.

$$E = mc^2 = 2.0 \times 10^{-8}\text{ kg} \times (3.00 \times 10^8\text{ m/s})^2 = 1.8 \times 10^9\text{ J} = 1.8\text{ GJ}$$

This decay is only 1.8 GJ's.

Consider EC.

$$^{195}_{79}\text{Au} + {}^{0}_{-1}\text{e} \rightarrow {}^{195}_{78}\text{Pt}$$

Remember that the e^- of EC begins as part of the atom itself. Thus, we can take the masses of the neutral atoms again.

$^{195}_{79}\text{Au}$	+	$^{0}_{-1}\text{e}$	$\rightarrow$	$^{195}_{78}\text{Pt}$
194.965038				194.964794

$$\Delta m = 194.964794\text{ g} - 194.965038\text{ g} = -0.000244\text{ g}$$

$$E = mc^2 = 2.44 \times 10^{-7}\text{ kg} \times (3.00 \times 10^8\text{ m/s})^2 = 2.20 \times 10^{10}\text{ J} = 22.0\text{ GJ}$$

There's quite a bit of kick to this decay, too.

Now, γ emission.

$$^{99m}_{43}Tc \rightarrow ^{99}_{43}Tc + \gamma$$

An excited state is higher in energy than the ground state, and that difference in energy is large enough to involve a significant mass. We start with the masses of the two atoms involved.

$^{99m}_{43}Tc$	$\rightarrow$	$^{99}_{43}Tc$	+	γ
98.906403		98.906250		

Find the change in mass between the two.

$$\Delta m = 98.906250 \text{ g} - 98.906403 \text{ g} = -0.000153 \text{ g}$$

The energy of the process can be calculated accordingly.

$$E = mc^2 = 1.53 \times 10^{-7} \text{ kg} \times (3.00 \times 10^8 \text{ m/s})^2 = 1.38 \times 10^{10} \text{ J} = 13.8 \text{ GJ}$$

That's another hefty amount of energy.

OK, let's summarize the approaches for finding Δm for the different types of decay.

- For α decay, take the masses of:
  neutral daughter atom + neutral ^{4}He – neutral parent atom
- For β^-, EC, or γ decays, take the masses of:
  neutral daughter atom – neutral parent atom

That Δm is then the mass of the energy of the decay, related by $E = mc^2$.

Let's see how you're doing.

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Example 1. Find the energy (in GJ) for one mole of the following decays.

A. $^{241}_{95}Am \rightarrow ^{237}_{93}Np + ^{4}_{2}\alpha$ (Masses: ^{241}Am 241.056827; ^{237}Np 237.048172; ^{4}He 4.002603)

B. $^{49}_{23}V + ^{0}_{-1}e \rightarrow ^{49}_{22}Ti$ (Masses: ^{49}V 48.948510; ^{49}Ti 48.947864)

. . . .

A. Go.

545 GJ. Not bad for a smoke detector, eh? OK, keep in mind that 545 GJ is for the complete decay of one mol of ^{241}Am. Your smoke detector might start with ~1.2 nmol which would then decay over several millennia, so don't worry about any meltdowns happening from that.

B. Go.

58.1 GJ.

The various calculations done so far give a taste of the massive energies involved in nuclear processes. We've done these calculations on a per-mole scale, using some unit of J, in order to allow comparisons to the many energies of the many chemical reactions which we have discussed in the past. Again, the energies of nuclear processes are outrageously high compared to the energies of chemical processes. But now we change our viewpoint from the mol scale to the atom scale, and we consider the energy of one single disintegration at a time. As noted at the end of Section 66.1,

> “ ...discussions in nuclear chemistry typically deal with the individual atom scale instead of the mole scale. There is some parallel to our prior discussions of electronic structure (Chapters 20 and 21) which were also on the per-atom scale. Be aware of this scale as we continue. ”

On the per-atom scale, the typical energy unit used in nuclear chemistry is the electron-volt, eV. This is not a common energy unit but it is convenient on the per-atom scale. Technically, it relates to electrical energy units: one eV is the energy of a unit charge (e.g., one electron) moving in a potential of one volt. Although it connects to electrical units, any energy unit can be applied to any form of energy. One eV is extremely small but, again, this is intended for the single particle scale. Here is the conversion connection to J.

$$\text{eV} = 1.602 \times 10^{-19}\ \text{J}$$

Since we are used to thinking of energies on the per-mole scale, here is a bit of perspective. A chemical reaction which involves one eV of energy for one molecule corresponds (via Avogadro) to 96.47 kJ for the reaction of one mole of those molecules. Thus, one eV is in the range (albeit low in the range) for chemical reaction energies; more generally, chemical energies will extend into several eV's, and some will go to one or more dozens of eV. Keep this perspective in mind. Returning to the combustion of C(*graph*) upstairs, the release of 393.52 kJ for one mole of C corresponds to 4.079 eV for one atom of C.

While on the per-atom scale, we will also use the atomic mass unit, u, and not g. As we work on this scale, it will be convenient to have a direct conversion factor between one u of mass and the equivalent energy in eV's. We derive this from $E = mc^2$ for a mass of one u as follows. First, convert the mass of one u to kg.

$$m = \text{one u} \times \frac{\text{g}}{6.022 \times 10^{23}\ \text{u}} \times \frac{\text{kg}}{10^3\ \text{g}} = 1.6605... \times 10^{-27}\ \text{kg}$$

Plug that into energy.

$$E = mc^2 = 1.6605... \times 10^{-27}\ \text{kg} \times (3.00 \times 10^8\ \text{m/s})^2 = 1.4945... \times 10^{-10}\ \text{J}$$

Convert to eV.

$$1.4945... \times 10^{-10}\ \text{J} \times \frac{\text{eV}}{1.602 \times 10^{-19}\ \text{J}}$$

You can punch this out and it will give 933 MeV, but I want to carry this out to more sigfigs to use for a conversion factor. When you start with more sigfigs in the values, the number comes to 931.5 MeV. This is the amount of energy which carries a mass of one u.

$$\text{one u} = 931.5\ \text{MeV}$$

You can now use this directly as a conversion factor, without going through $E = mc^2$ each time. To illustrate, let's repeat Example 1.

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Example 2. Find the energy (in MeV) for each of the following decays.

A. ${}^{241}_{95}\text{Am} \rightarrow {}^{237}_{93}\text{Np} + {}^{4}_{2}\alpha$ (Masses: ^{241}Am 241.056827; ^{237}Np 237.048172; ^{4}He 4.002603)

B. ${}^{49}_{23}\text{V} + {}^{0}_{-1}\text{e} \rightarrow {}^{49}_{22}\text{Ti}$ (Masses: ^{49}V 48.948510; ^{49}Ti 48.947864)

. . . .

We now seek the energy for a single disintegration event in each case. Notice that the same numbers are provided for masses as in Example 1; remember (Chapter 5) that any number for g/mol is the same number for u/atom (within our sigfig coverage).

A. You still need Δm, which you have from Example 1, Part A, but now you want this in u.

$$\Delta m = 237.048172\ \text{u} + 4.002603\ \text{u} - 241.056827\ \text{u} = -0.006052\ \text{u}$$

We now find the energy of that mass using only the conversion factor.

$$E = 0.006052\ \text{u} \times \frac{931.5\ \text{MeV}}{\text{u}} = 5.637\ \text{MeV}$$

This says that the decay of a single atom of ^{241}Am releases 5.637 MeV.

B. Your turn. Find Δm and then use the conversion factor.

You should get 0.602 MeV.

Both of these decays are in the MeV range, far in excess of the eV range of many chemical reactions. Chemical bonds are simply no match for a nuclear process. The only "typical" chemistry event which involves orbital electrons and which can approach these energies are electron excitations and relaxations involving core electrons. Keep this in mind for the next Section.

This will wrap up the math for now.

68.3 Aftermath

You are disintegrating hundreds of thousands of times per minute. Consider one atom of ^{14}C in some molecule of glucose, $C_6H_{12}O_6$, in some cell within your body. That molecule of glucose with one atom of ^{14}C will do the same chemical reactions as any other molecule of glucose. But all of a sudden that atom of ^{14}C happens to decay, forming an atom of ^{14}N and spitting out one β^-. That molecule is no longer a glucose molecule; now, it's a cation, $C_5NH_{12}O_6^+$, or it's even broken into smaller pieces. Your body will likely deal with that in an inconsequential manner (although that may not be true if it happens to other molecules in your system). The far more likely problem is the β^- which just went shooting past other molecules in the vicinity.

So just what does happen after a decay?

It depends.

As we have calculated, decays involve the release of a huge amount of energy. What happens to that energy? All α, β^-, and β^+ decays, as well as some EC decays, shoot out some particle in some direction into the surroundings with very high kinetic energy and correspondingly at very high speed. Instead of a particle, γ decay shoots out an extremely high energy photon. Furthermore, in many α decays and in many of the any β decays, the daughter is produced in an excited state which can then undergo γ decay in a subsequent step. In addition to all of these shootouts, the atom itself will often jerk in the other direction as a result of recoil; this will also have some energy associated with it. The recoil can be so violent that it breaks the atom free of all chemical bonds, completely hurling it out of a molecule or out of a solid lattice. The grand total of all of these energies is the energy of the decay which we have been calculating.

Let me elaborate on electron capture a bit more since it does not initially appear to shoot out anything. Again, EC involves capture of a core electron, usually from the 1*s* orbital. Removing a core electron from any atom is a very expensive process, and removing an electron from 1*s* takes the most energy because 1*s* is best in every atom. Part of the energy of the decay pays for removing the electron from that orbital. Once that electron is captured by a proton in the nucleus, the daughter atom is then left with a vacancy in the 1*s* orbital. An electron from a high energy orbital will then quickly relax down into that slot. This relaxation can release a photon, similar to relaxations described in Section 20.6 for H atoms, although those calculations only involved UV and vis photons. For atoms of higher atomic number, however, more protons in the nucleus mean stronger attractions to inner orbital electrons; in addition, there are more electrons in the atom and they are in higher orbitals, further out. As such, the relaxation to 1*s* can now be an extremely high energy relaxation, emitting an X-ray photon. But that's not the only option. As an alternative to X-ray emission, the energy of the relaxation can actually cause some other electron to be kicked out of its orbital and out of the atom completely. Thus, there is more to EC than just the name implies. Note that this now adds X-ray photons and ejected orbital electrons to the list of things which can shoot out of an atom following a decay event.

Given the high energies of the projectiles emitted in all categories of decay, a lot can happen in the follow-up when those particles and photons go rampaging into bystander atoms, molecules, or ions in the surroundings. The greatest havoc and harm of radioactive decay lies in what happens after the decay, and most of that, by far, involves orbital electrons in those bystanders who happen to be in the way. Only rarely will an emitted projectile strike a nucleus in another atom and cause an effect there; a nucleus is simply too small to be much of a target. The orbital electrons occupy the greatest volume, by far, of every atom. In reality, most decay projectiles pass by or through other atoms without having any effect at all but, somewhere along the way, there are going to be hits. The result of each hit is usually excitation or ionization: an electron in the bystander atom is excited to a higher energy level or an electron is kicked out of the bystander atom. An excitation or an ionization can be followed by a relaxation, ejecting now another photon from that atom. Additionally for ionizations, the newly ejected electron is often of such high energy that it will smack into yet another bystander atom, exciting or ionizing it. Thus, a string of things can happen, all from one single decay event. But it's not over yet. The original particle or photon from the decay is of such extremely high energy that it keeps going on and on, exciting and ionizing dozens to hundreds of thousands of other atoms in its path. As it goes, it loses the amount of energy for every excitation and ionization which it causes. Thus, with each hit, the original projectile loses a little bit of steam and, after enough hits, it's over. Once losing enough steam and slowing down enough, an α particle will rip two electrons from the surroundings and form a neutral atom of He. Once losing enough steam and slowing down enough, an ejected electron (β^-) will be picked up by some atom. For a positron, there's a twist since β^+ is the antimatter of the electron: once losing enough steam and slowing down enough, a positron will collide with an orbital electron and the two will be annihilated completely, spitting out two γ photons for the grand finale to their existence. For a γ photon, the photon doesn't slow down and it continues to travel at the speed of light in its medium; losing energy means increasing wavelength until it is finally and totally consumed in some encounter with some atom.

So how much damage are we talking about?

It depends.

The total damage will be based on the type of decay and the energy of the decay. Most of the energy of a decay is bourne by the ejected particle or photon. α particles are the big brutes: they pack the highest charge (2+), and they are the biggest and most massive of the decay particles. Because of these features, they impact far more atoms far more quickly into their path and, as such, they will stop sooner in their tracks. β^- and β^+ are of only a single charge, they are much smaller in size, and their mass is only 1/7,300 times the mass of an α; they will go further between interactions and they will travel a greater total distance through their surroundings. γ photons have no charge and no size; furthermore, they're photons and not typical particles, and that changes the manner of interaction. γ photons give the fewest interactions but they are consumed in far fewer hits; these travel the furthest in any medium. As for energies, α particles tend to carry the most wallop, commonly in the range of 4 - 7 MeV each, although some are less and some are more. β^- and β^+ particles, as well as γ photons, are usually lower in energy, from several hundred keV to a few MeV. Again, keep the perspective! One MeV = 1,000,000 eV and that is enormous compared to the several eV for a chemical reaction; you can also compare that to the 34 eV to ionize a typical molecule in air, or to the 38 eV which are needed to ionize one molecule of water. Anything close to one MeV can make a <u>big</u> impact on a <u>lot</u> of atoms! The trail of damage can be minute or quite long; here is a general comparison using an energy of 1 MeV for an α, a β^- and a γ entering into air from a decay.

The α particle will ionize ~6,000 atoms in one mm.
The β^- particle will ionize ~5 atoms in one mm.
The γ photon will only ionize ~1 atom in one <u>cm</u>.

This is just for the initial effects! These lengths are not necessarily the final distances of travel; this comparison just gives an idea of how fast each projectile is interacting and losing steam in air. For decays within liquids and solids, there are many more impacts in much shorter distances since there are many more atoms packed much more closely together in those phases.

Through any one specific medium, the total distance traveled will follow the trend $\alpha < \beta^- < \gamma$. The distance will depend strongly on the identity and phase of the medium, and density is a big factor. For illustration purposes, total travel distances for α and β^- are roughly one thousand times greater through air than through $H_2O(l)$. Unfortunately, "distance" traveled is not necessarily easy to measure. Due to its mass, the α particle barrels through any medium in a fairly straight path. β^-, β^+ and γ are deflected a lot off the atoms in the medium, and their paths can be more erratic. Because of this, it is common to refer to penetration or depth of travel. For a beam of decay projectiles passing into any medium, the γ photons will penetrate the furthest, followed by β^- or β^+; α doesn't make it very far at all in comparison. A piece of paper can stop α, but you'll need a bit more of concrete, 50 cm thick, to stop 99% of a γ beam (1 MeV). α carries the most punch, but it dumps it all quickly in its travel.

Remember your smoke detector? ^{241}Am emits α, and, for the most part, those are not getting out of the detector itself. On the other hand, ^{222}Rn also emits α. In the narrow passages of your lungs, an α can definitely hit lung tissue; therein lies the risk to you, along with additional α and β^- decays from the daughter steps.

All of these particles and photons can cause chemical changes in the atoms which are hit, and some of those chemical reactions are drastic. Consider excitations: as first noted in Section 21.2, atoms and molecules in excited states can react differently compared to when they are in the ground state. Consider ionizations: kicking an electron out of an atom within a neutral molecule now leaves a polyatomic cation, and that cation can react very differently from the neutral molecule. Furthermore, kicking an electron out of a diamagnetic substance will produce a paramagnetic substance (free radical) and, as first noted in Section 24.3 and again in Section 48.2, many paramagnetics are notoriously prone to reacting aggressively. And, all along the way, the energies of many of these events are more than adequate to start blowing apart any kind of chemical bond. For example, for some decay projectile going into $H_2O(l)$, a host of free radicals can be formed such as H_2O^+, OH, H, and even separate electrons themselves; all of these are very aggressive and they will react fast and further. The subsequent reactions can also involve solutes, if any are present.

It's a potential mess. If these things happen inside a living cell, they can cause harmful and even deadly reactions to occur. If these impact DNA, then cancer can result. You yourself are subject to these kinds of exposure. Naturally, and often unnaturally. 24/7/365.24. Fortunately, Nature provided you with elegant protections and fix-and-repair mechanisms but, unfortunately, they don't always catch everything. The far greatest exposure for the average human to harm from radioactivity (in the U.S. and in many other countries) is through natural sources, and the greatest single source, by far, is ^{222}Rn. Your body's ^{14}C and ^{40}K contents actually pose much less potential for harm than does environmental ^{222}Rn. As for unnatural sources, medical applications of radioactivity are very numerous. (This is not to be confused with a typical medical X-ray which does put out high energy photons, but those X-rays are generated electronically and not from a radioactive decay.) We've discussed γ-emitters and β^+-emitters for medical uses. Interestingly, even the PET projects use γ because the instrument detects the two γ photons which are formed following positron/electron annihilation. Both the γ-emitters and the PET methods are primarily used for radiodiagnostics, which means they use radiation for diagnosing a problem. ^{99m}Tc remains the most widely used nuclide for radiodiagnostics. But medical uses also include radiotherapy, which uses radiation to treat a problem. There are various approaches to this. One approach is to use an external radiation source, such as a high intensity decay source, which is then aimed at a particular tissue. Another approach uses a radioactive implant in the form of seeds or pellets (or other), which are implanted in or near a cancer for either the short term or the long term. Yet another approach uses an internally distributed compound which contains a radionuclide. As an example of this last method, consider ^{131}I for some thyroid treatments. Why I? Most iodine/iodide consumed by a human is taken up by the thyroid gland; this gland produces thyroid hormones containing 3 or 4 iodines per molecule which are then circulated throughout the entire body. These hormones affect a very wide range of cells and functions and are absolutely essential to health. But like so many other compounds that are essential to life, these compounds must be in the right amounts. If someone's thyroid does not produce enough of the hormones (hypothyroidism), they need to take hormone supplements. On the other hand, if someone's thyroid is too active and produces too much hormone (hyperthyroidism), then one treatment option is to reduce, or to kill, their thyroid gland. This can be done using ^{131}I. The person is administered a dose of this radionuclide, usually as the simple salt NaI, and the ^{131}I accumulates in the thyroid, where it does its nuke thing.

$$^{131}_{53}\mathrm{I} \rightarrow {}^{131}_{54}\mathrm{Xe} + {}^{0}_{-1}\beta \qquad t_{1/2} = 8.02\ \mathrm{d}$$

This kills at least some of the thyroid tissue. The dosage of ^{131}I which is administered to the patient can be so high that the patient is too radioactive to be safely around other people, especially children. Once treated, that person may be hypothyroid and must then take hormone supplements, or they may be within normal range of thyroid function. Besides hyperthyroidism, ^{131}I is also used to treat cases of thyroid cancer. ^{131}I is the most widely used, internally administered radiotherapeutic agent. It is also used as a radiodiagnostic for thyroid disorder.

Overall, on the grand scale of things, radioactive decay and its aftermath carries both a potential for great harm and a potential for benefit. Like so many other things, it's all in the balance.

Although the energies of decay are massively greater than the energies of chemical reactions, these are actually modest compared to the energies of nuclear reactions. We see that in the next Chapter.

Problems

The following values for masses (g or u) are needed.

^{4}He 4.002603	^{40}Ar 39.962383	^{79m}Br 78.918561	^{178}W 177.945886
^{14}C 14.003242	^{40}K 39.963998	^{79}Br 78.918338	^{218}Po 218.008971
^{14}N 14.003074	^{40}Ca 39.962591	^{178}Ta 177.945680	^{222}Rn 222.017577

1. True or false.
   a. In a chemical reaction, the change in mass is insignificant to the total masses involved.
   b. ^{60}Co has a greater mass than ^{60m}Co.
   c. A β^- particle penetrates further into a given substance than does an α particle.
   d. Of the various types of decay, γ decay typically gives off the most energy.

2. a. Write the equation for the α decay of ^{222}Rn.
   b. Calculate the energy (in GJ) for one mol of decays.
   c. Calculate the energy (in MeV) for one decay.

3. a. Write the equation for the β^- decay of ^{14}C.
   b. Calculate the energy (in GJ) for one mol of decays.
   c. Calculate the energy (in MeV) for one decay.

4. a. Write the equation for electron capture by ^{178}W.
   b. Calculate the energy (in GJ) for one mol of decays.
   c. Calculate the energy (in MeV) for one decay.

5. a. Write the equation for γ emission by ^{79m}Br.
   b. Calculate the energy (in GJ) for one mol of decays.
   c. Calculate the energy (in MeV) for one decay.

6. The ^{40}K within you decays either by electron capture or by β^- emission. Calculate the energy (in MeV) for one decay of each type.