Nuclear Chemistry and Electrochemistry

Everything You Need to Know

This packet will discuss the main things you need to know about nuclear chemistry. After you have gone through this packet, you will be pros who can build a nuclear reactor, clean up radioactive waste, and make an atomic bomb in your garages. There will be a quiz on this stuff next Thursday!

Let's get started with nuclear chemistry!

Part 1: What is nuclear chemistry?

Nuclear chemistry is the study of processes in which the nuclei of various atoms change in some way. There are several different ways in which this can happen:

- **Radioactive decay** is when an unstable nucleus breaks apart into smaller nuclei, or changes in some other way to make it more stable. All elements have radioactive isotopes in which the ratio of protons to neutrons makes the nuclei unstable. When radioactive decay occurs, these nuclei change into forms that are more stable.
  - All elements past uranium have NO stable isotopes. As a result, all of these elements undergo radioactive decay of some sort.

- **Nuclear fission** is a process by which a large atomic nucleus breaks up to form smaller ones. This process is accompanied by the production of a great deal of energy. This process is currently utilized in nuclear reactors and atomic bombs.

- **Nuclear fusion** is a process by which small nuclei combine to form larger ones. This process is accompanied by an even greater production of energy than nuclear fission. Nuclear fusion is the process that occurs in stars and in thermonuclear weapons (also known as “hydrogen bombs”).

To review, the symbols that are used to describe atomic nuclei have the following form: $^{\text{mass}}_{\text{number}}$U. In this symbol (which is also described as “uranium-238” or $^{238}$U), the isotope described is an atom of uranium that has an atomic mass of 238 amu and an atomic number of 92. Because atoms of uranium always have an atomic number of 92, this term is usually left off of this term.

Furthermore, to find the number of neutrons in this isotope, subtract the atomic number from the atomic mass, as we discussed earlier in the year. For example, there are 146 neutrons in U-238.

Sample Problems:

1) How many protons, neutrons, and electrons are in an atom of U-235?
2) Describe how radioactive decay differs from nuclear fission.
3) Which process, fusion, fission, or radioactive decay produces more energy? Explain.
Part 2: Nuclear decay

As mentioned before, one of the ways that nuclear reactions occur is radioactive decay. When radioactive decay occurs, the nuclei of an element either gain or lose pieces in order to gain a more stable ratio of protons to neutrons. Here are the following types of nuclear decay you need to know:

- **Alpha decay (α):** This is when a nucleus loses an alpha particle (a helium nucleus) to become more stable. One example of this reaction is the alpha decay of U-238:

\[ ^{238}_{92}U \rightarrow ^{4}\text{He} + ^{234}_{90}Th \]

Writing the equations of alpha decay is easy, once you know what to do. An example: Write the equation for the alpha decay of $^{244}_{94}$Pu:

- Step 1: Write the full symbol of the nuclide that's decaying. In this case, it's $^{244}_{94}$Pu.
- Step 2: One of the products of this reaction is an alpha particle, $^4\text{He}$. This gives us an equation that looks like this:

\[ ^{244}_{94}Pu \rightarrow ^{4}\text{He} + (\text{something}) \]

- Step 3: Figure out the other product. Because the law of conservation of mass does a pretty good job of describing how the world works, the mass of the particle will be 240 (the 244 from Pu minus the 4 from the alpha particle) and the atomic number will be 92 (the 94 from Pu minus the 2 from He – this element is uranium). This gives us a final equation of:

\[ ^{240}_{92}Pu \rightarrow ^{4}\text{He} + ^{236}_{90}U \]

- **Beta decay (β):** This is when a nucleus loses a beta particle, which is nothing more than an electron. For purposes of nuclear equations, beta particles are written with the following symbol: $^0_1e$. An example of beta decay occurs in lead-206:

\[ ^{206}_{82}Pb \rightarrow ^{206}_{83}Bi + ^0_1e \]

If you didn't know how to come up with this, simply use the same steps above to come up with the correct symbols.

- **Electron capture:** This is when a nucleus picks up an electron from the inner orbitals of the atom. Electron capture in boron-9 can be written via the following equation:

\[ ^9B + ^0_1e \rightarrow ^9\text{Be} \]

- **Positron emission:** This is when a nucleus emits a positron ($^0_1e$), lowering the atomic number by one but not changing the mass. This occurs in lithium-5:

\[ ^5\text{Li} \rightarrow ^0_1e + ^4\text{He} \]
• **Gamma emission:** This is when a nucleus gives off an energetic photon of light called a gamma ray ($\gamma$). When a gamma ray is emitted by a nucleus, neither the mass nor the symbol of the element changes—however, the resulting nucleus has less energy.

**Sample problems:**
1) Write the equation for the nuclear reaction that occurs when copper-62 emits an alpha particle.
2) Write the equation for the reaction that occurs when americium-243 undergoes positron emission.
3) Sometimes, several nuclear reactions take place one after the other until a stable nucleus is formed. If protactinium-235 undergoes beta decay, followed by electron capture, another beta decay, gamma emission, and alpha decay, what would the resulting element be?

**Part 3: Half lives**

As has been mentioned above, many nuclei aren’t very stable and undergo nuclear decay. However, if we have a single particle of a radioactive nuclide, we can't tell exactly when it will decay. We can, though, use statistics to determine roughly what fraction of particles will decay in a given length of time.

Think of it this way: Let's say that you have 100 pennies, all of which are heads. If you flip them all, you can predict that half of them will turn tails. You can’t tell which of these will be tails, only that about half of them will be. The same things happens with nuclear decay—you can’t tell which specific nuclei will decay, but you can use statistics to determine how many will decay in any period of time.

The idea that we use to describe the amount of time it takes for things to decay is that of half-life. The half life (given the symbol $t_{1/2}$) is defined as the amount of time it will take half of the radioactive particles to undergo decay. For example, if the half-life of an element is 5 minutes, and we have 80 grams of it in a container, we would expect there to be 40 grams of it after five minutes, 20 grams of it after 10 minutes, 10 grams of it after 15 minutes, 5 grams after 20 minutes, and so forth. For this compound, half of the stuff that remains goes away every five minutes.

There is, of course, an ugly equation that can be used to determine this. However, you'll find that the SOL uses examples that are simple enough that you can just figure them out using common sense. Kind of like the examples on the next page:
Sample problems:

1) If I have 344 grams of $^{236}$Tx and the half-life of this element is 45 minutes, how many grams of it will remain after 270 minutes?

2) If I start with 825 grams of $^{35}$Bp and 103 grams remain after 68 minutes, what is the half-life of $^{35}$Bp?

3) The half-life of $^{42}$Hi is 34 ms. If there are 0.00129 grams of it remaining after 544 ms, how much did I start with?

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Half-Life (25.3)

10. The half-life of tritium ($^3$H) is 12.3 years. If 48.0 mg of tritium is released from a nuclear power plant during the course of a mishap, what mass of the nuclide will remain after 49.2 years? After 98.4 years?

11. Technetium-104 decays by beta emission and has a half-life of 18 minutes. How many half-lives are there in 24 hours? How many mg of a 20.0 mg sample will remain after five half-lives?

12. Manganese-56 decays by beta emission and has a half-life of 2.6 hours. How many half-lives are there in 24 hours? How many mg of a 20.0 mg sample will remain after five half-lives?

13. A 20.0 g sample of thorium-234 has a half-life of 25 days. How much will remain as a percentage of the original sample after 90 days?
14. The half-life of polonium-218 is 3.0 minutes. If you start with 20.0 g, how long will it be before only 1.0 g remains?

15. A sample of an unknown radioisotope exhibits 8540 decays per second. After 350.0 minutes, the number of decays has decreased to 1250 per second. What is the half-life?

16. Phosphorous-32 has a half-life of 14.32 days. Write and graph an equation for the amount remaining of phosphorous-32 after \( t \) days if the sample initially contains 150.0 mg of phosphorous.

17. Plot the exponential decay curve for a period of five half-lives for the decay of thorium-234 given in Problem 13. How much time has elapsed when 30% of the original sample remains?

18. A rock once contained 1.0 mg of uranium-238, but now contains only 0.257 mg. Given that the half-life for uranium-238 is \( 4.5 \times 10^5 \) years, how old is the rock?

**Mixed Review**

19. A sample initially contains 150.0 mg of radon-222. After 11.4 days, the sample contains 18.7 mg of radon-222. Calculate the half-life.
20. Write a balanced nuclear equation for the positron emission of nitrogen-13.

21. Describe the penetration power of alpha, beta, and gamma radiation.

Graph It!

22. Plot the exponential decay curve for a period of six half-lives using the data given for technetium-104 in Problem 11. How much time has elapsed when 60% of the original sample remains?

23. What information about an atom can you use to predict whether or not it will be radioactive?

24. A bromine-80 nucleus can decay by gamma emission, positron emission, or electron capture. What is the product nucleus in each case?

26. The half-life of plutonium-239 is 24,000 years. What fraction of nuclear waste generated today will be present in the year 3000?