Nuclear Chemistry Cumulative Examination
Wednesday, 22 October 2o14

This examination consists of twenty questions on general information and properties of nuclei and nuclear reactions. The exam has a total of 100 points.

1. (25 points, 5 each) Provide **concise** and accurate answers to the following five general questions about the properties of nuclei and decay.

   (a) Approximately how many nuclei are stable against radioactive decay (within 10%)?

   (b) Write a **completely** balanced equation for the β^- decay of ${}^{14}_{6}$C. Be sure to include all emitted particles and any net charges on the products. This nucleus is critical for radiological dating of organic materials.

   (c) Write a **completely** balanced equation for the β^+ decay of ${}^{18}_{9}$F. Be sure to include all emitted particles and any net charges on the products. This nucleus is used extensively in PET imagining in Nuclear Medicine.

   (d) ${}^{238}_{92}$U is radioactive with a relatively long half-life and after a series of β^- and α decays turns into (only) one of the four stable lead isotopes [${}^{204}_{82}$Pb, ${}^{206}_{82}$Pb, ${}^{207}_{82}$Pb, ${}^{208}_{82}$Pb]. Which isotope does it form and why is it easy to predict which one without knowing the details of the decay chain?

   (e) People have estimated that approximately 90 PBq (2.4 MCi) each of ${}^{134}_{55}$Cs ($T_{1/2}$=2.0 yr) and ${}^{137}_{55}$Cs ($T_{1/2}$=30 yr) were released in the Fukushima disaster in March, 2011 and that the average level of ground contamination in California from this event was on the order of 100 Bq/m^2. Make an estimate of the ground contamination due to the lighter isotope, ^{134}Cs, in California in March, 2015. [see: http://cerea.enpc.fr/en/fukushima.html]

2. (25 points, 5 points each) Give a concise and accurate answer to each of the following short questions about the structure of very light nuclei.

   (a) There are only two conceivable values for the nuclear spin of a deuteron (^{2}H). What are the two values of the nuclear spin? One spin state is the ground state and the other is the lowest-lying excited state. Given that deuterium is NMR active, what is the ground state nuclear spin of deuterium?

   (b) The expected ground state nuclear spins of the dineutron (^{2}n) and ^{2}He are equal. What is the value of their ground state spins and why.

(c) The excited state of the deuteron with the dineutron (^{2}n) and ^{2}He make up a isospin triplet. Two partners in this group are mirror nuclei, which two are they? What is the defining property of mirror nuclei?

(d) The dineutron (^{2}n) and ^{2}He are both unbound. What, if any, implication does this fact have for the first excited state of the deuteron? Explain.

(e) The plan for "hot fusion" reactors of the future is to fuse two isotopes of hydrogen (deuterium ^{2}H and tritium ^{3}H) to generate energy. Write a **completely** balanced reaction for this fusion process showing the final products. Does this process lead to any radioactive products?

3. (25 points, 5 points each) Give a concise and accurate answer to each of the following short questions about the average properties of heavy nuclei.

(a) Nuclei with A>∼30 have *approximately* the same average binding energy per nucleon, regardless of it being a proton or neutron. What is the numerical value of this average binding energy per nucleon (within 10%)?

(b) Explain why the heaviest nuclei are unstable with respect to the emission of an alpha particle but the light nuclei are not.

(c) The liquid drop model is often used to describe the average properties of heavy nuclei. The mass density (mass/volume) and the number density (number/volume) of a drop of liquid are constants. Use the known properties of large nuclei to write an expression for the number density of a large nucleus. Simplify the expression, do you get a constant?

(d) The semi-empirical mass equation relies on the liquid drop model of the nucleus and only has five contributions (only five adjustable parameters). Indicate the theoretical basis for (or, at least, name) each of the five mathematical terms in the semi-empirical mass equation.

(e) The fission process leads to two product nuclei, of course. What is the most-likely fission fragment partner to the pesky ^{134}Cs isotope mentioned above? Explain your reasoning; will the partner have the same or different chemical behavior to cesium when released?

4. (25 points, 5 points each) Give a concise and accurate answer to each of the following short questions about the nuclear structure based on the shell model. (For reference, an energy level diagram is given below.)

(a) The shell model relies on filling neutrons and protons into separate potential energy wells that use so-called Woods-Saxon potential energy curve for the average nuclear reaction. Make a reasonably accurate sketch of the total potential energy well for neutrons and separately for protons in a heavy nucleus. Indicate a typical value for the depth of the potential well in MeV.

(b) What is the configuration of neutrons and protons predicted by the shell model for ^{7}Li? And what is the predicted ground state spin and parity of this nuclide?

(c) The lowest-lying excited state in ^{7}Li is the only bound excited state in this nucleus. What do you expect for the spin and parity of this sole excited state according to the shell model?

(d) The shell model predicts that mirror nuclei will have the same nuclear structure after correction for the difference in Coulomb energy between the pair of nuclei. What is the mirror nucleus for ^{7}Li? Will the ground state of the mirror be shifted up or down in energy compared to the ground state of ^{7}Li?

(e) Fact 1: Most of the chemical elements with an odd atomic number have only one stable isotope. Fact 2: Hydrogen, Lithium, Boron and Nitrogen are the only exceptions. Explain these facts using the shell model.