Science-1A Lab: Week 15, Wednesday & Friday, November 17 & 19, 2021
Nuclear Physics

Nuclear physics is a large and important topic that we must cover in about a week. I have done my best to give it to you in these notes and links. **This is for Wednesday and Friday.** It has lots to study, watch, and read. The videos about historic nuclear disasters and a tsunami are important events to know about.

To end the Japan side of World War II, the United States dropped two atom bombs on the cities of Hiroshima and Nagasaki, Japan. I usually start off the discussion by bringing in a booklet I bought at the Hiroshima Peace Memorial Museum when youth hosteling in Japan in 1967. It contains numerous images about the horror caused by that relatively small atomic bomb. The booklet is out of date, but there are many books and videos about the decision to drop those bombs and their lingering aftermath of nuclear radiation illness. You might search out and study some if you want to know more about the only use so far of atomic bombs in warfare.

In my high school days, we had drills designed to help us stay safe from an atomic attack during the Cold War with the Soviet Union. We were inundated with government pamphlets giving advice about building bomb shelters and how to protect ourselves from radiation. I studied those and wrote a term paper for my Government class where I pointed out how fruitless such actions would be in the event of a true nuclear war. I got an A+ on that report. Nuclear physics and historical events related to it are important for everyone to understand.

When we did our electrolysis and explosion, we added electrical energy to take apart H_2O and then got that energy back during the explosion. The electrolysis reaction $2\,H_2O(l)+\text{energy}\Rightarrow 2\,H_2(g)+O_2(g)$ shows that the water molecules are more tightly bound together than the hydrogen and oxygen molecules; we need to add energy to make that reaction proceed. When molecules (e.g. H_2O) are assembled from their individual constituent atoms (e.g. H, H and O), they snap together after getting close enough to overcome their energy barriers. The net energy change is called the **binding energy** of the molecule.

The same ideas apply to nuclear reactions except that the binding energy in nuclear reactions is about 10^5 times larger than in chemical reactions. That is why atomic bombs are so much more powerful than chemical bombs. Binding energy actually makes the mass of the assembled molecule or nucleus less than the sum of the masses of its separate parts. Einstein’s famous equation between mass changes and binding energy $E_{\text{binding}}=(\Delta m)c^2$ shows this. It barely produces observable effects in chemical reactions, but becomes significant in nuclear reactions; mass appears to be conserved in chemical reactions, but is clearly changed in nuclear reactions.

An introduction to nuclear physics with a rosy picture of peaceful uses of nuclear energy was given in the Disney program “Our Friend the Atom” at *https://www.youtube.com/watch?v=QRzl1wHc43I* which we watched during the Lab of Week-8. What was shown in that program is the background for what we are discussing here.

The nucleus of atoms contains both protons with a positive charge and neutrons with no charge. The neutrons add a "nuclear glue" that helps keep the protons from pushing each other apart. To fully describe a nucleus, both its proton count and neutron count must be specified. I actually like to use a redundant symbol that shows the atomic symbol, proton count, neutron count and also nucleon (proton plus neutron) count: ${}^{nucleons}_{protons}Symbol_{neutrons}$. This is redundant because the symbol must agree with the proton count and the nucleon count must be the sum of the number of protons plus the number of neutrons. For example, uranium has the symbol U and a proton count of 92, and usually has 146 neutrons ${}^{238}_{92}\mathrm{U}_{146}$, but some uranium nuclei have 143 neutrons ${}^{235}_{92}\mathrm{U}_{143}$. These can be uniquely specified as ${}^{238}\mathrm{U}$ and ${}^{235}\mathrm{U}$ because the U requires 92 protons, and the number of neutrons can be fund by subtraction, 146=238-92 and 143=235-92. Still, for educational purposes, I like specifying the symbol with all three numbers. Other examples are the three hydrogens ${}^{1}_{1}\mathrm{H}_{0}$, ${}^{2}_{1}\mathrm{H}_{1}$ and ${}^{3}_{1}\mathrm{H}_{2}$; two heliums ${}^{3}_{2}\mathrm{He}_{1}$ and ${}^{4}_{2}\mathrm{He}_{2}$; and three carbons ${}^{12}_{6}\mathrm{C}_{6}$, ${}^{13}_{6}\mathrm{C}_{7}$ and ${}^{14}_{6}\mathrm{C}_{8}$. In this note, we will also use the symbols n^0 , p^+ , e^- , e^+ , $\bar{\nu}_e$ and γ for neutron, proton, electron, **positron** (anti-electron), **anti-electron neutrino**, and high-energy photon (**gamma ray**). (**Neutrinos** are weird particles that I will not try to describe here.)

One basic nuclear reactions is

$$n^0\Rightarrow p^+ + e^- + \bar{\nu}_e + \text{energy} \quad .$$

Here, a *lone* **neutron** spontaneously disintegrates into a **proton**, an **electron**, and an **anti-electron neutrino**. The products on the right side of this reaction have less total mass than the **neutron** with the mass difference becoming their kinetic energy. This reaction is called a **beta decay**, and the emitted electron is called a **beta particle** often shown with the symbol β^- or more simply just β . Those high-energy electrons are also called **beta rays**.

Neutrons *that are part of a nucleus* are usually stable and do not undergo this beta decay reaction; the "nuclear glue" holding a nucleus together tends to suppress neutron decay. If, however, a nucleus has too many neutrons, this reaction will turn one of its neutrons into a proton, and the nucleus will spit out a beta ray.

An important term describing nuclear reactions is the **half-life** of the reaction. Nuclear reactions happen with a timing that depends on chance. We cannot say that any particular *lone* neutron will decay in a certain amount of time, but only that if we measure the decay times of a large number of them, half will have undergone a decay after 881.5 seconds. After another 881.5 seconds, half of the remaining neutrons will have decayed. Of an initial 1 million neutrons, only about $10^6\cdot\left(\frac{1}{2}\right)^{10}=977$ will remain after 10 half-lives (8815 s). This 881.5-s value is called the **half-life** for that neutron decay reaction.

In another type of nuclear reaction, an electron and a positron can meet and annihilate each other. The reaction is

$$e^+ + e^- \Rightarrow 2\gamma \quad .$$

The electron and positron masses completely vanish to become the energy $E_{2\gamma}=(m_{e^+}+m_{e^-})c^2$ of the pair of very high-energy photons called **gamma rays**. Two gamma rays must be emitted in opposite directions to satisfy the conservation of momentum law if the electrons had no momentum before the reaction. More often, gamma rays are produced when nucleons rearrange themselves in a nucleus, just as much less-energetic light photons are emitted when electrons rearrange themselves in the shells of an atom.

Another kind of nuclear decay is where a large nucleus emits 2 protons bound to 2 neutrons as a single chunk. This chunk is called an **alpha particle** (α-particle) and is, in fact, just a helium nucleus ${}^{4}_{2}\mathrm{He}_2$. An example of an alpha decay is when uranium spontaneously becomes thorium in the reaction

$${}^{238}_{92}\mathrm{U}_{146}\Rightarrow{}^{234}_{90}\mathrm{Th}_{144}+{}^{4}_{2}\mathrm{He}_2+\mathrm{energy}$$

This decay has a half-life of 4.468 x 10^9 years. While visiting a research laboratory in 1966, I held a 10 kg mass of very pure ${}^{238}_{92}U_{146}$ without concern. In the 10 seconds I held it, one out of every 1.4 x 10^{17} uranium atoms will have decayed, but only those right at the surface can emit alpha particles that reach my hands, and those alpha particles cannot penetrate skin. Such pure ${}^{238}_{92}U_{146}$ metal is called **depleted uranium**.

The most dramatic nuclear reactions are those that combine small nuclei together (**nuclear fusion**) and those that cause large nuclei to break apart (**nuclear fission**). Both of these reactions release energy and produce products that are more tightly bound. The most tightly-bound nuclei are those in the mid-range of size around iron ${}^{56}_{26}\mathrm{Fe}_{30}$.

This is clearly shown by a graph of nuclear binding energy per nucleon vs. the proton number of elements. See the upper graph at *https://yosemitefoothills.com/Science-1A/Handouts/Week-14/BindingEnergyCurveAndUraniumDecayChain.pdf* where the most stable nuclei with the greatest binding energy per nucleon are at the top of the hump in the center. The unit used for energy is MeV which is about 10^5 times greater than typical chemical binding energies.

At this point, please carefully read the 4-page handout at *https://yosemitefoothills.com/Science-1A/Handouts/Week-14/NuclearReactions.pdf* .
It explains many related aspects of nuclear physics including cosmic rays, other natural radioactive sources, carbon dating, radiation poisoning, atomic (fission) bombs and hydrogen (fusion) bombs.

The Disney program used a Geiger counter to detect radioactivity. We have one at the college, and if it is turned on and simply left alone with no obvious sources of radiation, it will typically click an average of 16 times per minute as it is detects cosmic rays and the normal background radioactivity from granite rocks in cement. The cosmic ray rate is not constant because there are fluctuations in the rate that very high energy particles from the Sun and other sources in the universe strike our upper atmosphere. Those create showers of less-energetic nuclear particles that reach the surface of the Earth.

Counting these Geiger counter clicks by hand is impractical for longer periods of time so I opened our Geiger counter and connected it to a microprocessor that could measure the time of each click to within 1 ms. That microprocessor was in turn connected to a Raspberry Pi computer to store the thousands of data points. The result was two large graphs of counts vs. time. They are at
https://yosemitefoothills.com/Science-1A/LabNotesAndLinks/RadioactivityAndCosmicRays/dataOut-June-26-July-6-2013.gif
and
https://yosemitefoothills.com/Science-1A/LabNotesAndLinks/RadioactivityAndCosmicRays/dataOut-July-14-July-30-2013.gif .
In them, the horizontal grid line intervals are 20 counts/second while the vertical line intervals mark hours, with days separated by vertical red lines. When the data reaches the right border, they are continued at the left side with a vertical offset. Ten days are on the first graph and sixteen more days are on the second. The message you should get from these graphs is that we are constantly being bombarded by cosmic rays which can dramatically increase at times in “cosmic ray showers”. The Geiger counter detector is about 300 times smaller than our bodies, so we actually get hit by about 6000 cosmic rays per second. This has been happening throughout the evolution of humans, so our bodies are actually amazingly good at fixing the damage caused by cosmic rays.

With our Geiger counter and a ${}^{14}_{6}C_8$ beta-ray source, we are able to show that a few sheets of paper can block beta rays. Both beta rays and alpha rays are blocked by our skin. We can also show that gamma ray photons easily penetrate a hand by using a sample of uranium ore that emits gamma rays.

There are many applications of radioactivity in medicine. Some are described in the handout at
https://yosemitefoothills.com/Science-1A/Handouts/Week-14/MedicalImaging.pdf .
Reading this will help you understand what these techniques do if your doctor advises their use.

Finally, you need to understand the downside of nuclear power by watching YouTube videos about the nuclear disasters at Three-Mile Island, Chernobyl, and Fukushima. The following list is 3-1/2 hours of videos that are worth watching. These are the last ones to watch during this course. They are at:

1. The China Syndrome (1979) ORIGINAL TRAILER (2 min 2 s, The real movie lasted about 2 hours)
https://www.youtube.com/watch?v=bIGH1AfIS18
This fictional movie was, by pure chance, released just 12 days before the Three Mile Island accident listed next.
I do NOT expect you to watch the full movie since you would need to pay.

2. Three Mile Island Documentary (42 min 47 s) with intro to Chernobyl disaster.
https://www.youtube.com/watch?v=C_HWrVeYP5E

3. Full Documentary What Really Happened at Chernobyl National Geographic Documentary HD (44 min 16 s)
https://www.youtube.com/watch?v=AZ4qOMN527s

4. CHERNOBYL DISASTER - An Inside Look - 3D (8 min 18 s)
https://www.youtube.com/watch?v=fwtNvnWZjZY

5. The story of Chernobyl's New Safe Confinement (23 min 19 s)
https://www.youtube.com/watch?v=mdnutU2m71o

6. CNN: Entire towns engulfed by tsunami (18 min 13 s)
https://www.youtube.com/watch?v=zxm050h0k2I

7. Full Documentary on Fukushima Nuclear Disaster (43 min 26 s)
https://www.youtube.com/watch?v=2zsZPPxEy1s

8. Understanding the accident of Fukushima Daiichi (13 min 1 s)
https://www.youtube.com/watch?v=YBNFvZ6Vr2U

People promoting nuclear power tend to underplay the chance for accidents. Also, nuclear reactors produce very dangerous radioactive waste that must be safely stored for hundreds of years without contaminating ground water.

As solar and wind power become more common, arguments will be made that we need nuclear power to maintain electrical energy flow when "the sun doesn’t shine and the wind doesn’t blow". An alternative, however, is massive battery storage, and learning to be less wasteful use of energy.

9. The Future Of Energy Storage Beyond Lithium Ion (14 min 21 s)
https://www.youtube.com/watch?v=EoTVtB-cSps

These are the last videos for this course. Report that you read these notes and watched all 9 videos and you will earn double credit for this lab.