FINAL VERSION

1. Blackbody radiation is emitted by all objects that have finite temperature. We will consider a number of items that you are familiar with and deduce the blackbody radiation they emit.

   (a) YOU! Your temperature is 37 ^oC, or 310 K. Find the peak wavelength and frequency of light emitted by you. What range of the spectrum (radio, microwave, infrared, visible, ultraviolet, xray, gammaray) is this light found in?

   (b) Your stove coil turns red hot. Take 600 nm as the peak wavelength of this light. What is the temperature of the stove coil?

   (c) Penzias and Wilson discovered that radio static is actually blackbody radiation from the cold outreaches of space. They set the temperature of space at 2.7 K (don't fret over this, space is not completely empty so it can have temperature). What is the peak frequency of the blackbody radiation from cold space?

2. A Helium atom consists of it's nucleus (^4_2He) and 2 electrons. The energy levels in this nucleus are not precisely the same as though in the Bohr formula since the electrons are not only affected by the Z=2 nucleus, but they are also affected by each other.

   However, if one of the electrons from a He atom is removed, this positively charged ion (a ^4_2He nucleus plus only ONE electron), is indeed quite accurately described by the Bohr formula. We will calculate a number of things for this Z=2 ion.

   (a) If the electron is in the ground state, what energy photon is necessary to remove it?

   (b) If the electron is in the n=2 state, what energy photon is necessary to remove it?

   (c) What energy photon is released if the electron drops from the n=3 to the n=2 state?

3. Bohr derived his famous formula for quantized energy levels in an atom using the condition that angular momentum was quantized. deBroglie instead assumed that electron waves (of known wavelength) must fit into orbits in much the way that waves on a guitar fit within the string.

   (a) Write down the Bohr condition on angular momentum.

   (b) Write down the deBroglie condition on wavelength.

   (c) Show that these two conditions are indeed the same.

4. No two electrons can occupy identically the same quantum state. For this reason, not all electrons on a given atom can be in the n=1 state, some of them must be in higher states. As one considers bigger and bigger atoms, the n=1 level will fill up, followed by n=2, followed by n=3, and so on...

   (a) We will consider that atom that completely fills the n=2 level. Each electron in this atom will have a set of 4 quantum numbers (n, l, m_l, m_s). Please fill in the table below specifying all four quantum numbers for each of these electrons:

n	l	m_l	m_s

   (b) What element is this in the periodic table?

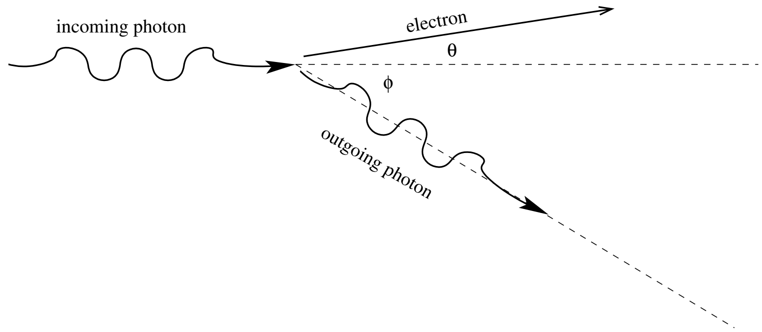
   (c) What special property results from having the n=2 level completely full?

5. Some particular material has a work function of 5 eV. For this material:

   (a) Calculate the lowest frequency photon that can remove an electron from this material.

   (b) Calculate the wavelength of a photon that removes electrons from the material such that the electrons leave with 8 eV as thier maximum kinetic energy.

6. Shown in the figure below is a compton scattering event in which a high energy photon is deflected by its interaction with an electron. The photon is deflected by the angle ϕ, and the electron (initially at rest) is ejected at the angle θ.



(a) Let the initial energy of the photon by 5 keV. What is the initial wavelength of the photon? What is the momentum of the initial photon?

(b) If the angle ϕ is 30 degrees, calculate the wavelength of the scattered photon.

(c) Find the momentum **vector** (yes, x and y components) of the photon as it exits the collision zone.

(d) Find the momentum vector of the electron as it exits the collision zone.

(e) What is the direction, θ, of the electron?

(f) What is the energy of the electron?

(g) What is the wavelength of the electron?

7. Close study of some heavy nuclei showed that they were not stable and emitted "rays". This was different from X-rays (that were purposely made by man) since these special elements voluntarily made radiation instead of by coercion. Different types of these rays were labelled with the greek letters $\alpha, \beta, and \gamma$. We now know better what these rays are:

   (a) Identify what each of the following are made of:

      i. alpha rays.

      ii. beta rays.

      iii. gamma rays.

   (b) In free space, a neutron has a lifetime of only 10 minutes! Write down the equation that shows the decay of a neutron. Your equation should look like "$n \rightarrow something + something + something$".

   (c) In a ${}^{12}_{6}C$ nucleus, the neutrons cannot decay. Explain why.

   (d) In a ${}^{14}_{6}C$ nucleus, the "last" neutron can decay. Write an equation that describes this decay in the form "${}^{14}_{6}C \rightarrow something + something + something$".

   (e) Would the decay listed in the previous step be considered alpha, beta, or gamma decay?

   (f) A proton in free space does not decay. However, in the nucleus ${}^{11}_{6}C$ it can indeed decay. Write an equation for this decay in the form "${}^{11}_{6}C \rightarrow something + something + something$".

   (g) Living material maintains the ratio $\frac{{}^{14}_{6}C}{{}^{12}_{6}C} \sim 1.3 \times 10^{-12}$. ${}^{14}_{6}C$ has a 5730 year half-life.

      i. Calculate the $\frac{{}^{14}_{6}C}{{}^{12}_{6}C}$ ratio for a sample of material that is 2,000 years old.

      ii. Calculate the $\frac{{}^{14}_{6}C}{{}^{12}_{6}C}$ ratio for a sample of material that is 20,000 years old.

      iii. Calculate the $\frac{{}^{14}_{6}C}{{}^{12}_{6}C}$ ratio for a sample of material that is 65 Million years old.

      iv. Explain why Carbon dating is **not** used for dinosaur bones.

   (h) ${}^{229}_{90}Th$ (Thorium) decays by an alpha decay. Write an equation for this decay in the form "${}^{229}_{90}Th \rightarrow something + something + something$". The following information might be helpful:

   $({}_{86}Rn,\ {}_{87}Fr,\ {}_{88}Ra,\ {}_{89}Ac,\ {}_{90}Th,\ {}_{91}Pa,\ {}_{92}U,\ {}_{93}Np)$.

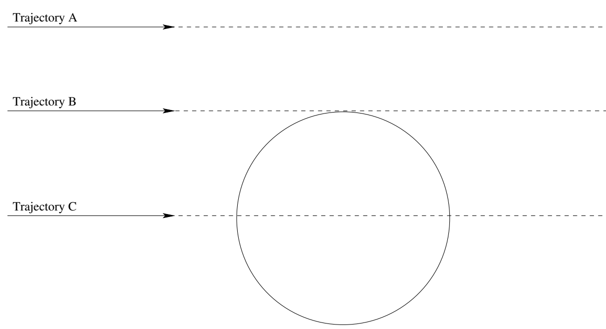
8. Early in the 20^{th} century, much was known about chemistry and the periodic table (an outgrowth Mendeleev's Table), but less was known about the interior structure of an individual atom. Rutherford's famous experiment (performed by his assistants Geiger and Marsden) was the first look into the atom in detail and the results were surprising. Answering the questions below will teach you about how this historic event leads us to a better picture of the atom and more precisely, the nucleus.

   (a) Using Avagadro's number (6×10^{23}) and the density of Gold ($19.3\frac{grams}{cm^3}$), find the volume of one atom of gold ($^{197}_{79}Au$).

   (b) Assuming a Gold atom is a sphere, calculate the radius of this Gold atom using the result from the previous step.

   (c) Describe in 2-3 sentences the atom according to the Thomson "Plum Pudding" model (now known to be an incorrect description). Use the volume/radius from the previous steps somewhere in your reply.

   (d) Shown in the figure below is a Thomson model atom and three possible incoming trajectories of an alpha particle (Helium nucleus). Which of these trajectories experiences the greatest deflection upon passing the Au atom?



   (e) Calculations of expected deflections of the alpha particle from the Thomson model showed that the maximum expected deflection was 0.02^o. Imagine the surprise when the data showed scatterings of more that 90^o!! In the Thomson model of the atom one could not generate a force that was strong enough to make such a deflection. Explain in 3-4 sentences how the Thomson model was changed (by Rutherford) so that a single atom could generate larger forces ion the alpha particle.

   (f) In Rutherford's, famous formula, he assumed that the nucleus had zero size (a perfect mathematical point). Explain in 2-3 sentences why his formula failed when using higher energy alpha particles.

   (g) Calculate all the following:

      i. The radius of a Gold ($^{197}_{79}Au$) nucleus.

ii. The radius of an Alpha (^4_2He) particle.

iii. Calculate the energy of the alpha particle necessary to bring it so close to a Au nucleus that the edges touch (*i.e.* distance between nuclei = $R_{Au} + R_{He}$).

(h) Explain what happens to the alpha particle if it comes closer to the Au nucleus than the result calculated in the previous step.

(i) What new force was introduced into physics to explain the fate of the high energy alpha particle.

9. Now that we know about the nuclear force we can answer all of the following:

   (a) Consider two nuclei. The electric force repels these two nuclei. The nuclear force attracts them. Since the nuclear force is much stronger why do these two not get atracted and immediately fuse?

   (b) OK, now we know why nuclei on a tabletop do not fuse (*i.e.* cold fusion). Now consider two hydrogen nuclei (*i.e.* two protons) each of which has a charge of $q = 1.602 \times 10^{-19}\ C$. What would be the **electric** potential energy if these were separated by a distance of $r = 1\ fm = 1 \times 10^{-15}\ m$.

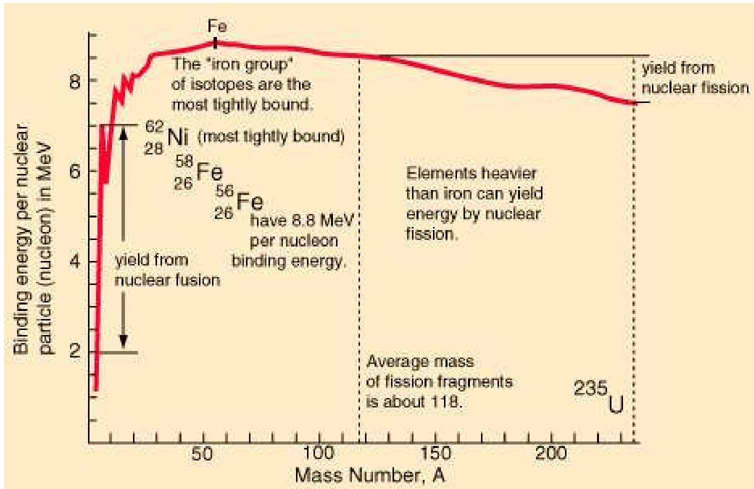
   (c) The separation distance in the previous step of this problem is small enough to experience the nuclear force. Convert this amount of energy into a temperature using the Boltzmann constant ($k = 1.38 \times 10^{-23}\ \frac{J}{K}$).

   (d) The temperature on the surface of the sun is 6000 K. The temperature in the center of the sun is about 15,000,000 K. Explain in 2-3 sentences why the sun has nuclear fusion reactions and your stove does not.

   (e) The simplest reaction in the sub involves fusing two protons. However, no nucleus exists with two protons and no neutrons. Write the reaction that actually occurs and provides the energy of the sun in the form "$p + p \rightarrow$ *something* + *something* + *something*"

   (f) In the previous equation, only one of the reaction products can reach us here on earth. Which one?

10. Inside a nucleus, the nuclear force attracts (strongly) but the electric force repels (weakly). The nuclear binding energy curve is shown in the figure below:



(a) Explain, using the characteristics of the nuclear and electric forces why this curve rises then falls.

(b) Explain, using the characteristics of the nuclear and electric forces, why the rise is steeper than the fall.

(c) Which is the most tightly nucleus?

(d) To release energy from a Uranium nucleus, would you use fission or fusion? Explain using the nuclear binding energy curve.

(e) To release energy from two deuterons (^2_1H), would you use fission or fusion? Explain using the nuclear binding energy curve.

(f) Which of the previous two reactions releases the most energy? Explain.

(g) One atomic mass unit is $u = 1.6605402 \times 10^{-27}\ kg$. The rest mass of a deuteron ^2_1H is 2.0141018 u and the rest mass of a helium ^4_2He nucleus is 4.026032 u. Calculate the energy released in the reaction $^2_1H + ^2_1H \rightarrow ^4_2He$.

(h) The result from the previous step is the energy released by a single nuclear reaction. What is the energy released is 2 moles of ^2_1H were used (*i.e.* producing 1 mole of ^4_2He).

(i) What is the environmental impact of He?

11. Nuclear reactors and bombs operate on the principle of a chain reaction induced by nuclear fission.

   (a) Explain the process of nuclear fission:

      i. Which nuclei will spontaneously fission, large ones or small ones?

      ii. Compare the reaction products of fission with alpha, beta, or gamma, decay.

   (b) $^{235}_{92}U$ produces 2-3 neutrons when it fissions in addition to two large nuclear fragments. Why are these neutrons important for a reactor or bomb?

   (c) Explain the following terms:

      i. Critical mass.

      ii. Sub-critical mass.

      iii. Super-critical mass.

   (d) You have just learned that this morning your nearby nuclear power plant was at supercritical mass for a short time. Is this normal? Explain.

   (e) What was the mechanism in the "Little Boy" bomb by which the Uranium was brought rapidly from Sub-critical to Super-critical?

   (f) What trick is used in a power plant reactor so that it can run with less highly purified Uranium (*i.e.* not as purely $^{235}_{92}U$ but actually having mostly $^{238}_{92}U$, much closer to the natural abundance?

   (g) A breeder reactor uses the $^{238}_{92}U$ in it's core to "breed" additional fuel and thereby keep the reactor running for more years before the spent rods need to be replaced. Write the equation for the nuclear reaction the produces more fuel in the form:
   "$^{238}_{92}U + something \rightarrow something + something$".

12. The "rule of thumb" for an NMR device is that protons will achieve resonance at a frequency of 42.58 MHz when they are immersed in a magnetic field of 1.0 Tesla. Assume that a patient is placed in a magnetic field, B, whose strength varies with position, x, according to the formula $B(x) = 1.0\ Tesla + 0.1 \frac{Tesla}{m} x$.

    (a) Especially strong resonant signals are received coming back from the patient for frequencies of 43.00 MHz and 45.00 MHz. Find the locations in x that produce these signals.

    (b) The doctor can think of this technique as one that "maps the location of water" inside the patient. Explain why.

13. PET scanning is an additional method of medical imaging that involves the annihilation of a positron inside a patient producing two photons. The mass of a positron is the same as the mass of an electron, $m_e = 9.109 \times 10^{-31}\ kg$.

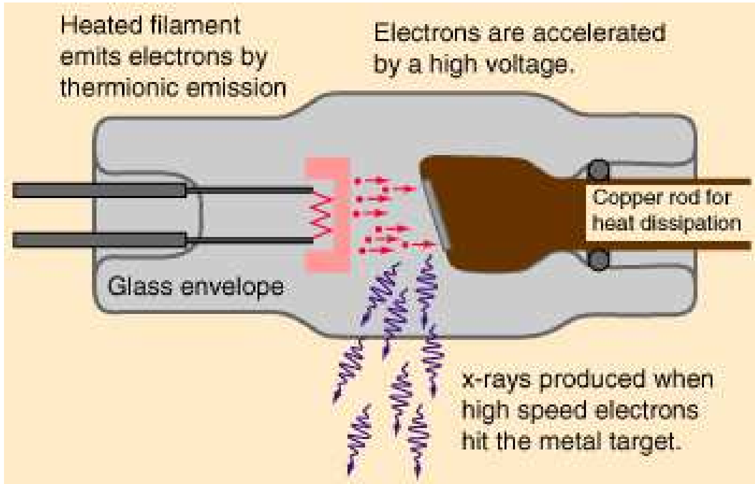
  (a) What is the mass energy of the positron?

  (b) How much energy is released during the annihilation process?

  (c) This energy is divided equally between the two photons. What is the frequency of each of these photons?

  (d) Explain in 2-3 sentences why PET imaging is higher resolution than SPECT.

14. Shown in the picture below is an X-ray tube.



(a) Where do the electrons come from?

(b) Why are the electrons pushed to the right?

(c) What physical process causes the electron energy to turn into EM radiation?

(d) Suppose the accelerating voltage of the X-ray tube were 70,000 Volts.

i. What is the energy of each electron as it strikes the tungsten/copper plate?

ii. Assuming that all this energy goes into a single photon, what is the frequency of that photon?

iii. What is the wavelength of that photon?

15. You and a friend are each holding meter sticks that are held so as to align with the "z" axis. You are also both holding clocks. Your friend boards a train travelling at 0.8c in the Z direction:

    (a) You watch your clock and your friends. When your clock shows 5 minutes have elapsed, you look at your friend's clock. How much time seems to have elapsed on that clock?

    (b) Your friend looks at his clock and waits until it says (to him) that 5 minutes have passed. He then looks at your clock. How much time does he claim has elapsed on your clock?

    (c) You look at his meter stick and measure it. How long does his meter stick appear to you?

    (d) He looks at your meter stick. How long does your meter stick appear to him?

    (e) Your friend's trip will take him a distance of 4 light-years to reach another star. When he reaches that star indeed, his clock reads as though it took too little time to get there. You claim that it is because his clock ran slowly. He, on the other hand, has a completely different reason why he seems to have arrived early. What is his reasoning that the trip was so short?