The 67th Compton Lecture Series at the University of Chicago

Seeing and Believing: Detection, Measurement, and Inference in Experimental Physics

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Notes and thoughts for Lecture 2, April 12 2008

Introduction: The purpose of today’s lecture

The purpose of today’s lecture is, primarily, to spend some time thinking about what is taking place all around (and inside of) us at scales too small for us to see. We will begin by reminding ourselves of the fundamental particles that make up ordinary matter, and the fundamental forces that govern their interactions. Matter at molecular, atomic and subatomic scales is buzzing with activity: everything is constantly in motion, undergoing interactions, radiating, and absorbing radiation. Taking this room as our current environment, we will catalog the radiation that is being emitted by objects (and people) around us, as well as the types of radiation that are being absorbed within it, or just passing through (which we will take up in more detail next week).

Some of the radiation in this room, if we could detect it, might give us insights into unanswered questions at the cutting edge of physics. Most of it represents well-understood physical phenomena. However, even the least mysterious radiation in this room is relevant to the purposes of these lectures. Supposing that you wanted to build a detector someplace on the earth, the “radiation environment” surrounding your detector is likely to be similar to the radiation environment in this room. A central challenge to “seeing” a particular radiation signal in your detector, and then “believing” that you are seeing it (and not something else) is finding ways to deal with this background radiation.

Part 1: What are we made up of?

As a launching point for today’s discussion, let’s look in some detail at the physics taking place at small scales inside the human body. On a chemical level our bodies are made up of largely water and carbon compounds, with some trace minerals tossed in. Each molecule is made of one or more atoms picked from the menu offered by the periodic table. An inventory of the atomic constituents of the typical human body would show it mostly made up of oxygen, hydrogen, and carbon. We have appreciable numbers of nitrogen, calcium, phosphorous, potassium, sulfur, sodium, chlorine, and magnesium atoms in there too. Then there are dozens of trace elements. Some of them have important roles in the body (like iron), and some of them are just along for the ride, like trace quantities of rubidium, strontium, and uranium.
Each of the atoms within us, itself, composed of a dense nucleus containing neutrons and protons, surrounded by a diffuse cloud of electrons. The identity of the atom (whether it is carbon or oxygen or sodium or uranium) is determined by the number of protons in the nucleus. Its chemical properties (how it binds with other atoms) are determined by the arrangement of electrons in the atom. The number of electrons that surround the nucleus is matched to the number of protons, in a neutral atom. These electrons buzz around the nucleus in clouds, but can only do so in a discrete set of possible ways that is described in the fundamental theory of quantum mechanics. Because a full description of the quantum mechanics of the atom is outside the scope of this lecture, I’ll resort to using some hand-wavy descriptions. If you imagine the electrons orbiting the nucleus in an atom, these electrons can only exist in ‘states’ with specific energies, which specify some features of their orbits. For the purposes of a simple cartoon, energy ‘states’ or ‘levels’ can be visualized as orbits at different radii, with those at higher radii representing the higher energy states for the electron. Electrons in an atom can only gain or lose energy by transitioning between these specific states, via absorption or emission of a photon with exactly the amount of energy representing the difference between the two atomic levels.

Nuclei for a particular atomic species, for example carbon, can often have different numbers of neutrons in the nuclei. This has no appreciable effect on the chemical or macroscopic behavior of the atom, but it is one of several factors that influence whether the nucleus of that atom is stable or likely to decay. Atoms or nuclei of a particular atomic species that have different numbers of neutrons are called different isotopes of the same element. As an example, your body contains at least three isotopes of carbon. The most common is carbon-12 (carbon with 6 neutrons and 6 protons, summing to 12 total nuclear particles). About 1% of the carbon in your body is carbon-13, which has an extra neutron but is stable. Some smaller fraction is the unstable carbon-14 that is famous for allowing radioactive dating of biological materials. The nucleons (neutrons and protons) in a nucleus are not held in a static configuration, but move around in a nuclear cloud. The nucleus is characterized by a set of quantum mechanical energy states much like the atom, such that nuclei can only gain or lose energy in discrete amounts corresponding to the differences between nuclear energy levels.

Most of the physics taking place in ordinary matter in a room like this one can be explained by understanding what goes on between atoms and within atoms. This means understanding the behavior of neutrons, protons, electrons, photons (light) and, as we saw last week, sometimes neutrinos. However, if we want to get a little more technical about it, protons and neutrons are not themselves fundamental particles. Each proton is made up of a trio of quarks, two ‘up’ quarks and one ‘down’ quarks (the names of
quarks are silly and meaningless). Each neutron is made of two down quarks and one up quark.

One of the triumphs of physics in the last 100 years is the development of a ‘standard model’ of particle physics that describes all of the fundamental particles that we know about, as well as the ways that they can interact. There are actually not very many truly ‘fundamental’ particles, although they can combine in many ways to make a variety of compound particles. The entire particle content of the universe (as far as we now know) can be summed up with the following table:

There are three major classes of particles in this table: leptons, quarks, and force carriers. Note that the standard model also includes antiparticles for all of these particles, although the antiparticle can in some cases be the same as the particle itself (the photon is one example). Quarks and leptons differ in how they are affected by the different fundamental forces of nature. Notice that all of ordinary matter is made up of particles from the first column of quarks and leptons. That is, the huge variety of materials and objects around us (and in most other environments in the universe) is made up entirely of up and down quarks and electrons (with electron-type neutrinos showing up in some processes). The other quarks and leptons are harder to come by in natural environments, although we can create them in accelerators.

The other classification of particles is the so-called ‘force carriers’. With the (extremely huge and interesting) caveat that a quantum theory of gravity has not been worked out yet, we envision forces between particles being conveyed by the exchange of ‘force quanta’ or ‘force carriers’. These are particles that do the dirty work of making two particles attract or repel or scatter off of each other. For our purposes, the most important of these is the ubiquitous photon, which ‘carries’ the electromagnetic force. You might picture, for example, two electrons tossing photons at each other, absorbing each other’s photons, and experiencing a backlash or repulsion because of it. It’s hard to go much further with an intuitive picture of how force carriers work, though, since how do you make an exchange of photons cause an attractive force? A whole Compton lecture series could be (and has been) devoted to explaining how all of this really works. To understand detectors and detection, we can sidestep some of this and just describe how the forces affect ordinary atoms and nuclei and how they relate to radiation production and radiation detection.
Part 2: Forces at work inside ordinary matter

In terms of our everyday experience, gravity has an obviousness that can’t be claimed by any of the other fundamental forces in nature. Stuff falls. You don’t fly away into space. However, gravity has almost no importance on the subatomic scale, where the remaining three forces (the electromagnetic, strong, and weak forces) dominate the physics. For the purposes of being complete, I’ll point out that gravity is an attractive force between all massive objects, and it has infinite range, so that massive objects at any distance from one another can still feel a force of attraction, however minute.

The force that is arguably truly most important to our everyday experience is the electromagnetic force. The electromagnetic force operating in ordinary matter explains all of chemistry, the signaling processes that communicate information in cells and through our bodies, and the ways that our senses take in information about the world. Light, sometimes just called ‘electromagnetic energy’ because of its role in carrying the electromagnetic force, obviously enables sight. The electromagnetic attractive and repulsive forces between the atoms in neighboring materials ultimately cause the friction and texture that we register when we touch objects. Arguments could be made that all of our senses ultimately rely on the electromagnetic force.

The electromagnetic force between two charged particles is about 40 orders of magnitude stronger than the gravitational force between them. It is also an infinite-range force. The electromagnetic force affects any particle with electric charge, so that includes all of the quarks and half of the leptons (neutrinos are neutral, as you might guess from their name). Like charges repel, and opposite charges attract.

Given the repulsive nature of the electromagnetic force between two like-charged particles, it is somewhat miraculous that nuclei can actually exist. How is it possible to assemble multiple positively charged protons into a small space without all of them repelling and flying apart? The strong nuclear force explains this, and gets its name from the strength it must have to bind nuclei together despite the electromagnetic repulsion of the protons. Neutrons and protons (and any other particles made up of quarks) experience the strong force, which functions in the nucleus as an attractive force operating over very small distances.

The more protons a nucleus has, the more powerful the electromagnetic repulsion becomes, and the more neutrons are needed to maintain the delicate balance. Heavier nuclei therefore tend to have more neutrons in them than protons. For each element, there is a specific ratio of neutrons to protons that provides the optimal stability and lowest energy in the nucleus. It’s interesting to note that there is an upper limit to the number of protons you can put in a nucleus (and therefore a limit to the total number of stable elements in the periodic table) that comes about because of the short range of the nuclear force. In a large nucleus with many protons, a proton at the edge of the nucleus feels all of the repulsion from every proton in the nucleus, but only feels the attraction from its nearest neighbors. For nuclei with a lot of protons, the repulsion of the many protons will win out over the attraction of the few nearest neighbor protons or neutrons. This limit is at around 83 protons (bismuth), and any element beyond that in the periodic table will be unstable.
A stable nucleus is one that has the best possible number of neutrons to balance its protons, and has no extra energy associated with the neutrons and protons sloshing around more than they absolutely have to (to obey the uncertainty principle – a whole story in itself!). If a nucleus does not have the best possible balance of neutrons to protons, the situation can often be corrected through the intervention of the ‘weak force’. The weak force is harder to picture than the other three fundamental forces, since it does not involve attraction or repulsion. It has such a short range that it essentially just operates within a single particle itself. It can be thought of as a means by which particles are capable of changing their identity, provided conditions are favorable. A neutron, left on its own, will always transmute or ‘decay’ into a proton by the weak force (protons have slightly less mass than neutrons, and thus this is the energetically favored state). Within a nucleus, it is often more energetically favorable for that neutron to remain a neutron, unless there are too many neutrons. If a nucleus has more than its preferred number of neutrons, then one or more of them may transmute to protons in the phenomenon of ‘beta decay’, which we encountered last week. If a nucleus has fewer neutrons than the most favorable number, a related phenomenon called ‘beta-plus decay’ can transmute a proton into a neutron and correct the situation. We’ll return to discussing decays shortly.

**Part 3: What are you radiating?**

a) *Thermal electromagnetic emission*

A central feature of the electromagnetic force is that any time that a charged particle changes speed or direction, it radiates electromagnetic energy (light of some form). Likewise, charged particles can absorb electromagnetic radiation and be accelerated, or exchange photons to bounce off of one another. A central feature of any material that is not held at absolute zero temperature is that all of the particles within it are constantly moving, and this energy of motion is what we call heat. From these facts, it’s apparent that all matter that is held at some non-zero temperature must be constantly radiating electromagnetic energy, since it is full of charged particles undergoing lots of random motions.

What are the characteristics of this ‘thermal’ radiation, caused by the random motions of charges in objects? Well, if the temperature of the object is higher, we expect that the particles within the object are, on average, moving faster. Charges that are moving faster are capable of radiating higher-energy photons, which are photons with a shorter wavelength or a higher frequency. We therefore expect that as an object gets hotter, it will tend to radiate higher frequency light. In a typical massive object like a person, there are enough charged particles available to move around in enough ways that the object is essentially capable of either absorbing or emitting light of almost any frequency. This contrasts with our simple picture of a single atom, for example, which is really only able to absorb or emit light at specific frequencies corresponding to the energy levels of the atom. If you have enough atoms or molecules or free electrons around, there will always be ways for some of the charges to be excited vibrationally or rotationally or in some other way so that light of any frequency has a way to be either absorbed or emitted.

Objects with higher temperatures will tend to radiate higher-frequency light, but objects of all temperatures radiate a fairly wide range of energies of electromagnetic radiation. Real physical objects like the ones in
this room are not perfectly capable of absorbing and radiating at all possible frequencies, but they do a pretty good job. An object that is a perfect absorber and radiator at all electromagnetic frequencies is an idealization that physicists call a ‘black body’. Every ‘black body’ emits radiation with the same characteristic shape, a ‘universal thermal spectrum’, called the Planck spectrum. The first description of the quantum nature of thermal electromagnetic radiation, leading to correct derivation of this spectrum, was a critical step in the development of quantum theory. A sketch of the Planck spectrum is shown below. What is shown is the intensity of the radiation emitted by three objects at different temperatures, as a function of the frequency of the light emitted. Hotter objects emit more light at all frequencies, but also the peak of the curve (where the intensity is highest) moves higher in frequency. Only the temperature of the object needs to be known in order to completely predict its thermal electromagnetic radiation emission.

The human body is at a temperature of about 300 K. If we view the human body as a black body, then the peak of the radiation is at a frequency in the infrared region of the electromagnetic spectrum. So, you are always glowing in the infrared, which is why sensors capable of picking up infrared radiation are a useful tool for seeing you in the dark. You’re also emitting some electromagnetic radiation at longer wavelengths (lower frequencies), according to the Planck spectrum.

b) Radioactivity (emission of radiation from nuclei)

Where thermal electromagnetic emission is a property of any material that has a non-zero temperature and contains a bunch of electrical charges, radioactivity is a feature of a material that depends on exactly what elements and isotopes it contains. Thermal radiation is emitted over a continuous range of energies (translating to a continuous range of frequencies of electromagnetic radiation). Nuclear radiation, like radiation from individual atomic transitions, is always emitted with characteristic energies corresponding to the energy differences between nuclear energy levels.

The nuclei that make up everything around us were originally produced in the deep furnaces inside of stars, where protons from hydrogen are fused together into heavier elements, and during the intense events called supernovae, when stars explode. Some of these production mechanisms result in nuclei that do not have the ideal balance of neutrons and protons, which explains where heavy, long-lived unstable elements like uranium originated. There are a few natural processes that also can take perfectly stable nuclei and initiate
transmutations of these into unstable nuclei. These are high-energy processes like those that take place in accelerators or when very high energy particles from space (cosmic rays) collide with nuclei in the atmosphere. This latter phenomenon explains the production of radioactive carbon-14 in the upper atmosphere. Whatever their origin, unstable nuclei are present in small numbers in pretty much everything around us. It is exceptionally difficult to find a material that has no unstable nuclei within it: everything in this room is somewhat radioactive (even though mostly at a low level).

If you plot the number of neutrons vs. the number of protons for every nucleus, you will find that the stable nuclei all lie along a particular line (the thick black line in the sketch below). This illustrates the fact that heavier nuclei tend to prefer to have more neutrons than protons. Any nucleus that happens to be far from this line will undergo a succession of decays (sometimes over extremely long periods of time like billions of years) until it has transformed into one that lies along this ‘line of stability’.

Nuclei with large excesses of protons or neutrons can simply eject the excess particles, but most unstable nuclei will tend to decay by emitting an alpha particle (two protons and two neutrons), or by changing a neutron into a proton (beta decay) or vice versa (beta-plus decay). These decay mechanisms are like chess moves on the neutron-vs-proton grid. The chess moves allowed are shown below:
Let’s start with considering alpha decay. Heavy nuclei tend to decay by alpha emission to reduce their overall size. After emitting the alpha particle (the radiation from the decay), the nucleus is typically still in an excited state – you can think of the particles in the nucleus as having some extra energy of motion. Alpha decays are usually followed by one or more gamma decays, in which the nucleus settles down by emitting the excess radiation as high-energy photons. Alpha decays also tend to leave nuclei on the neutron-rich side of the line of stability, so they are frequently followed by one or more beta decays some time later.

Beta decay, as we learned last week, transforms a neutron into a proton, emitting a brand new electron (the beta particle) and a neutrino (actually an electron anti-neutrino) in the process. The electron and the neutrino make up the radiation emitted in this sort of decay. As with alpha decays, the nucleus is often left in an excited state and emits a few ‘gamma rays’ or high energy photons to settle down. Beta-plus decay is a very similar process, whereby a proton transforms to a neutron and emits a positron (the antiparticle to the electron) and an electron neutrino.

Gamma decay has been mentioned already as a way for nuclei to ‘settle down’ if they have excess energy distributed among the protons and neutrons. It commonly follows other sorts of decay. An interesting related process is internal conversion, where instead of emitting the excess energy in the form of electromagnetic radiation, the nucleus instead essentially kicks one of the atomic electrons out of the atom, carrying the energy with it. This type of decay produces an energetic electron as radiation, but is not formally ‘beta decay’. Internal conversion explains the source of the energy spectrum lines that we saw last week in Chadwick’s measurements of the supposed beta decay spectrum from radium.

Two more interesting decay mechanisms are electron capture and fission. In electron capture, a proton ‘captures’ an atomic electron and merges with it through the weak interaction to produce a neutron (and a neutrino, of course). The neutrino is the only radiation emitted immediately from this process, although it is often followed by gamma decays. Fission is a rare sort of decay whereby a very heavy nucleus splits into two modestly-sized daughter nuclei. Typically it is accompanied by the spontaneous ejection of some of the extra neutrons, so neutrons are some of the initial radiation products of fission. Fission daughter nuclei are neutron-rich, so there are many prompt beta decays that follow every fission event, and many gamma decays as the beta-decaying daughter nuclei settle down. These beta and gamma decays are the source of the intense (potentially lethal) radiation associated with fission-based nuclear technologies like bombs or reactors.

Of these processes, which are actually taking place within your body right now? Well, it would be reasonable to speculate that all of them take place at some time. Trace quantities of heavy elements like uranium and thorium are present everywhere on the earth, and tiny quantities of radioactive elements produced in nuclear bomb explosions (like strontium, for example) are absorbed from the environment and built into our bones (in very tiny amounts). Trace heavy elements would allow for a small amount of alpha radiation and even fission taking place in your body. Alpha particles are unlikely to escape your body, since alpha radiation is very easily absorbed in ordinary matter (unfortunately, since it’s also very damaging to our cells).
The majority of the radioactivity in your body is due to a radioactive isotope of potassium, potassium-40. It’s closely followed by carbon-14. Both of these are beta emitters, and between them your body is radiation something like 8000 beta particles (and antineutrinos!) per second! Potassium-40 is also capable of undergoing beta-plus decays, which means that antimatter (positrons, or anti-electrons) is being produced within your body at some small rate. Because you are always consuming potassium and carbon, you are always replenishing the quantities of these radioactive isotopes in your body, so your level of radioactivity is relatively constant.

**Conclusions**

We’ve just taken a whirlwind tour of subatomic physics in order to explore radiation processes in the typical human body, or in the objects in this room. We have not exhausted all of the types of radiation that you will find in this room. For example, there are lots of types of electromagnetic radiation produced by technologies, such as radio, television, and cell phone signals. Particle radiation from space (cosmic rays) is also penetrating the atmosphere and the ceiling and streaming through this space, including a large number of muon particles. Neutrinos from all sorts of sources are streaming through us in unimaginable numbers – many billions per second passing through a space the size of your little finger. Neutrinos produced in the big bang are also lingering around, as well as possibly other big bang relic particles that are postulated to constitute the so-called dark matter. Gravity waves are also passing through us, although of all the types of radiation those might be the hardest to detect in this room! Next week we’ll ask about some of the forms of radiation that are currently of interest to physicists, and consider what challenges there are to detecting them in the presence of all of the rest of the radiation around us.

A summary of a range of common natural radiation types and their energies is provided on the last page.

**References:**

The best places to look for introductory subatomic physics information (without resorting to textbooks) are the numerous very useful webpages on these topics. Some of my favorites:

hyperphysics: [http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html](http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html) Has some good introductory material on quantum mechanics and the Planck spectrum.

particle adventure (from LBL): [http://particleadventure.org/](http://particleadventure.org/) This is a good site for understanding particles and forces.