Part 1: Introductory comments reflecting on the purpose of these lectures

“The purpose of these lectures is to make accessible some of the remarkable recent developments in physical science to the non-specialized public, and to share with laymen some of the intellectual and cultural excitement associated with scientific developments that may affect in some way the lives of all of us and are a significant part of our cultural heritage.” (from the Compton Lectures website)

Before we get into the fun stuff with the 67th Compton Lecture Series, I would like to reflect for a moment about the statement of purpose above. Why exactly is it important for scientists to make our work accessible to the public? Why is it important for you to know about ‘remarkable recent developments’ in physics, especially when they are often remote from everyday experience, or obvious practical applications? This is an interesting question, given that much of what was ‘cutting edge’ at the beginning of the Compton Lectures in 1976 is still beyond the level of awareness most individuals have about physics these days. How important can any of this stuff be, really, if the ‘cutting edge’ discoveries of the day don’t even percolate into general consciousness over 30 years?

There are a lot of obvious and valid answers to the question of why something like the Compton Lecture Series is valuable, and they will also differ from lecturer to lecturer and audience member to audience member. Before designing this lecture series, I thought for a long time about why I thought it was a valuable thing for me to spend the next ten weeks talking physics to this audience, and how to choose a topic that would emphasize the things I found most valuable about it. I am hoping you’ll agree with my arguments and find the topic I’ve chosen as interesting, rich, and significant as I do.

My argument goes something like this:

The pursuit of answers to basic questions about the world is fundamentally human, like literature, art or music. Therefore it’s inherently something that people find fascinating, and it’s important to celebrate that. Where art and literature tap into the human needs to create, relate, interpret, and communicate, science taps into our basic human curiosity and our ways of finding things out about the world. Science is about
inquiring, observing, and reasoning, which are things we do every day. Very ordinary, human things. Science just formalizes them a bit, focuses on specific questions, and argues with a bit more detail than you usually need to come to conclusions about things in everyday life.

Yet, if you read about the latest fundamental physics discoveries in a newspaper, odds are that the basic human side of science is lost in a swirl of unfamiliar vocabulary, abstract and grandiose-sounding claims, and blurry intermingleings of established knowledge and creative speculation. It was important to me, in selecting a topic for these lectures, to come back to earth a little bit and celebrate the simple acts of observation and reasoning that are common to all science, as well as to the daily lives of all human beings. Even when the papers announce spectacular-sounding evidence for Dark Energy, or new searches for something called the ‘God particle’, the reality usually boils down to a group of people attempting to detect some radiation signal from nature and make sense of it. Hence the emphasis, in these lectures, on the process of detection and how we make inferences based on what we see in our detectors.

The acts of observing (through detectors) and reasoning (generally using statistics) anchor exotic-sounding science to the activities of ordinary humans. At the same time, the process of detecting radiation itself anchors even the most remote physics to the physics of the everyday. Even if we are trying to learn something about dark matter, or gravity waves from the early universe, or particles that are only produced in extreme environments, we have no choice but to build our detectors out of more pedestrian things (ordinary matter), and base them on known physical principles (our understanding of subatomic particles and radiation and how they interact). This is one of the reasons that radiation detection is a favorite subject of mine. Simultaneous with exploring the ways that we learn about distant places in the universe, or physics of elusive or rare particles, we can’t help but also explore the world that is immediately around us, buzzing around at the atomic and subatomic scales. In the context of today’s technologies, an awareness of subatomic physics has more than just a general appeal to the intellect; it’s also important for understanding technological devices that are newly omnipresent.

Another aim of this lecture series is to convey something of the reasoning processes between detection of a signal to conclusions about a physical phenomenon. Whether or not we are aware of it, confidence in the reasoning of scientists is important to decisions we make personally and collectively about health, economics, and politics. The Compton Lecture Series is neither the place to explore the philosophical descriptions of scientific epistemology, nor the place to address the scientific process as it applies to hot-button political issues such as climate change. However, in part because of the importance of scientific reasoning in the bigger picture, I’d like to place some emphasis on scientific inference as it applies to experimental physics. By learning about detectors and about some of the simple (statistical) principles used to analyze detected signals, we will address, in some very small way, how we build up knowledge about the physical world and convince ourselves we should really believe it.
Part 2: A brief interlude to define ‘radiation’ and get some feedback from you

At this point in today’s lecture, I’ll be asking for your help in giving me some feedback (by filling in the questionnaire at the end of this set of notes) on what your goals are in coming to these lectures. I’ll also be asking a science question, and this is something I would like to do regularly. It helps me to have a feel for the level of background in this audience and to identify problems with the vocabulary that I’m using. If you have a strong physics background, you might find these questions oversimplified or ambiguous. If so, feel free to rewrite the questions in a more specific way and answer your own versions. If you have no idea how to answer the question in any form, please say so! These questions are not things that I expect most people to know off the top of their heads, and it’s helpful for me to see that, so that I don’t make the lectures too technical.

In these lectures, I’m going to use the word ‘radiation’ a lot. In casual usage physicists often use this word quite differently. It also has different meanings to public audiences than it does to physicists. When I use it, here is what I mean:

**Radiation:** energy traveling through space in the form of waves or particles.

For our usage in this lecture series, if something you (or some random physicist) might think of as a particle or wave is being emitted by some physical process and traveling through space, that’s a form of radiation. These particles and waves are the ‘signals’ we hope to detect in the wide variety of detectors that we will discuss in this lecture series.

Part 3: Beta decay and the neutrino: a tale of two particle detectors

To advertise some of the ideas to come later in this lecture series, let’s start with my favorite ‘detector story’: the early investigations into beta decay and the eventual discovery of a new particle called the neutrino.

Given that regular sunlight is a form of radiation that we detect with our eyes every day, there is no point in human history that you can cite as the invention of the first radiation detector. However, it wasn’t until the turn of the 20th century that laboratory radiation detectors were invented for the exploration of phenomena at scales much smaller than we can naturally see. Beginning with Becquerel’s discovery in 1896 of a form of radiation emitted spontaneously from uranium ore, there was an explosion of activity in physics and chemistry to understand this ‘radioactivity’ and its origin in the atom.

Becquerel, Marie and Pierre Curie, Ernest Rutherford, and other early investigators initially detected radiation from the atom using photographic plates. Photographic plates contain tiny crystals of silver salts (containing molecules of, for example, silver and bromine). Light (or other radiation capable of depositing energy in the crystals) can break up some of the molecules, and the free silver atoms distributed across the plate form a ‘latent image’ that can be enhanced through chemical development processes. A typical
experiment involved taking a sample of a radioactive material like uranium or radium, setting up some ‘obstacles’ for the radiation to go through (like electric or magnetic fields, or thin strips of material), and then looking at blobs on a photographic plate where that radiation had interacted with the silver salts. A second technique was also used to detect radiation from the atom, based on the phenomenon of ionization. When charged particles go through a gas, they can strip some atoms of their electrons. The atoms of the gas are then ‘ionized’ and have an overall positive charge. An early instrument called an electroscope could detect the ionization of a gas, from the motion of a small gold foil that initially given some static electrical charge. The charged gold foil would stand up a bit, like your hair does when there is a lot of static electricity, and the charges in the ionized gas would make it relax. Marie Curie’s PhD thesis summarized the state of knowledge about radioactivity in a drawing similar to this one in 1906:

![Diagram of alpha, beta, and gamma rays]

This figure contains quite a lot of information about the phenomena observed. Three types of radiation had been discovered, called ‘alpha’, ‘beta’, and ‘gamma’ rays (alpha and beta ‘particles’, and gamma ‘rays’, in today’s vocabulary). Alpha rays could be easily stopped by a small bit of material placed between the radioactive sample and the detectors. Beta rays were harder to stop. Gamma rays were not appreciably attenuated by material between the source and the detector. Alpha and beta rays were observed to deflect in opposite directions in a magnetic field, demonstrating that they had opposite charges (with the beta rays being negative). Gamma rays were uncharged. All of this was determined using the simple detection methods described above.

Experimenters in the early 1900s were curious about the origin of these rays and their properties. If they represented energy being emitted from the atom, then through Einstein’s famous $E=mc^2$ equation, their emission would actually reduce the mass of the sample and represent a fundamental transformation of the material in some way. The energy carried by these rays (both through their mass and the energy of their motion – essentially their speed) was of fundamental interest. How do you measure the energy of a particle using the simple techniques that the Curies and their colleagues had in hand? For the charged particles, the degree of deflection in a known magnetic field could be used. More energetic rays would be deflected less by a given applied field.

Early experiments of this sort showed fairly definitively that alpha rays from a specific radioactive material came in discrete energies characteristic of each material. Researchers assumed that beta rays must be
similar, and some experiments showed that they were. However, some experiments showed that the beta rays emitted from a single material came in a wide range of energies. For a number of years starting around 1911, an enormous controversy surrounded the energy ‘spectrum’ of beta rays, at the same time as the nature of the atom and its constituents was being unraveled by many researchers. Measurements remained crude and ambiguous, a consequence of the simplicity of the technologies available at the time. Experiments appeared to be contradictory: some showed that beta rays had specific energies for given materials, and some showed a continuum of energies. While this controversy progressed, Rutherford’s scattering experiments and developments in fundamental physics theory were leading to our modern picture of the atom and its nucleus.

In 1913 and 1914, Chadwick performed an experiment using a technology recently invented by Hans Geiger, called a particle ‘counter’, and finally settled the question: beta particles (as they were now known) were emitted in a range of energies from typical emitting materials. The Geiger counter is one of the most famous particle detectors of all time and also one of the simplest (we will describe one in detail in a couple of weeks). It operates by amplifying the amount of ionization caused by a charged particle going through a gas, and then collecting the charges in that ionized gas to create an electrical pulse.

The experimental setup that Chadwick used is illustrated below. For the initial spectrum measurement, nothing was placed in the position marked ‘B’. The beta particles were emitted at ‘Q’, bent by a magnetic field, and then passed through a small aperture into a Geiger counter. As the magnetic field strength was varied, the number of particles that made it through the aperture were counted.

![Experimental setup diagram](figure from Controversy and Consensus: Nuclear Beta Decay 1911-1934, Aaserud, Kragh, Rudinger, and Stuewer, editors)

Chadwick observed a continuous spectrum from a radium sample, with a few strong ‘lines’ (concentrations of beta particles of a few specific energies) superimposed on top. This was similar to things that had been seen less clearly by previous researchers. He made a stronger case for the continuous beta spectrum than previous researchers had, by employing cross-checks and reasoning techniques that are so common in
modern experimental physics that we rarely call them out for special notice. For example, one important question was to make sure that the particles he detected were really coming from the source and not from random other places, or from beta particles taking different paths than expected within the apparatus. To test this, he placed some lead in the position marked ‘B’ in the figure. He showed that he measured very few particles when the main beam was blocked, and they couldn’t explain the continuous spectrum. This was a measurement of the ‘background’ to his experiment. The other convincing thing that he did was to change the detector to make sure that the result he was seeing wasn’t a feature of the detector itself. He repeated the measurement using an ionization detector like those that had been used in early experiments. These simple cross-checks made a powerful argument that the spectrum was continuous (we now know that the beta decay spectrum is always continuous, and the lines in Chadwick’s spectrum come from another type of nuclear decay that emits electrons, called internal conversion).

By 1914, the atom was known to include a central core called the nucleus, and alpha, beta, and gamma radiation were believed to originate in the nucleus. The discrete energies of alpha rays were evidence that while nuclei can transform, they can only do so in limited ways. Every nucleus of a given type (or isotope, specified by its number of neutrons and protons) has the same constituents, the same energy (at rest), and the same probability for making transitions to other types of nuclei. When these transitions occur, they can only occur by emitting certain particles at certain energies. A central principle governing radioactive decays (and all processes in physics) is the conservation of energy, and the discrete alpha lines are consequences of this: the alpha has to carry with it all of the energy that the nucleus needed to expel in order to transition from one well-defined initial state to another well-defined final state. This amount of energy is always the same for a particular type of transition.

The continuous beta decay spectrum was surprising, because it suggested (rather threateningly) that perhaps energy conservation was not obeyed in beta decays. In a beta decay, a neutron in a nucleus spontaneously transforms into a proton and emits an electron (the beta particle). The electron should carry with it all of the energy expelled by the nucleus during this transition. The fastest electrons emitted from a given type of nucleus presumably do; but what of the ones lower down in the spectrum? Did they simply lose their energy to the environment somehow? Was something else going on?

In 1930, theorist Wolfgang Pauli proposed a ‘desperate way out’ of this dilemma in a famous letter to his colleagues, the ‘Radioactive Ladies and Gentlemen’ who were assembled for a meeting that he could not attend. He suggested that the beta decay involved an unseen third party, a new particle that was later dubbed the ‘neutrino’. This particle would have to be neutral for the conservation of electric charge to work out in the decay, and it would have to be very penetrating (that is, able to go through matter very easily) to have avoided detection up to this point.

Some years later, another theorist, Enrico Fermi, formalized the theory of this proposed particle. As more was learned about the atom, the basic proposal went as follows. In beta decay, a neutron transforms into a proton and emits both an electron and one of these new neutrino particles. The neutrino, to satisfy the theory and experiments up to that point, had to be almost or completely without mass, electrically neutral, and so disinclined to interact any further with matter after its initial creation that it could travel through a
light year of lead without being stopped. These were the conclusions of the speculative theory concocted by Fermi and others over the decades after Chadwick’s experiment, to explain the continuous beta spectrum.

All processes of radiation production and detection are fundamentally random, a fact we will explore further as we get deeper into these lectures. It is impossible to predict when an individual atom will decay. In the same way, it is impossible to predict that a particular electron will ‘interact’ in the gas in a detector and ionize a gas to the degree needed for us to detect it. We can only make statistical statements about the probabilities that these events will occur. From the point of view of detecting radiation, we want to maximize the number of times that we actually see something. So, we want to pick a detector such that the radiation we’re measuring has a high probability of triggering a detection. This is often a matter of knowing the underlying physics of how the radiation will interact with the matter in the detector, a subject we will explore in much detail.

But for the purposes of this story, what of the neutrino? Its probability of interacting with the matter in a typical detector was expected to be abysmally small from the theory. The only method proposed for detecting a neutrino was to look for ‘inverse beta decay’. This is essentially the reverse of the process that created the neutrino in the first place. The neutrino is absorbed by a proton, creating a neutron and requiring the simultaneous creation of a positron (and anti-electron, to balance out the charge conservation). How would you look for this, especially given that it would be extremely rare if it happened at all? If you have no idea, you’re in good company. There were no serious proposals among the best physicists for decades.

In the 1950s, two significant developments changed this. First, a new detector technology was invented: liquid scintillators. In a scintillating material, the atoms absorb some of the energy as charged particles pass through, and then re-emit this energy as visible light that can then be detected by some light-sensitive detectors (we’ll hash out the details in a couple of weeks). Scintillators are charged-particle detectors. They would have to detect the ‘secondary’ radiation produced when the neutrino initiated a transformation of a target proton into a neutron, and the positron went on to annihilate with an electron, and the resulting photons collided with electrons and then these electrons excited the scintillator material to make more light which is then detected by another detector... (it takes a few steps). This sounds fairly indirect (although not from the perspective of modern particle detectors). However, the key advantage to liquid scintillator detectors is that they can be made very large, scaling the mass of the detector to several tons to increase the rate of possible detections.

Nowadays, it is not particularly unusual for a detector to be as large as a room, but in the 1950s, nobody had every considered a reason for doing this. Until the quest to detect the neutrino. If you know that the particle you are trying to detect has an extremely low chance of actually doing anything in your detector, the only way you have a hope of actually seeing any of them is by making the source of the radiation as intense as possible and making the detector as large as possible. You need billions and billions of neutrinos to pass through your detector, and you need a detector huge enough that there are billions and billions of protons that they have a little bit of a chance of hitting. Then, even if the probability for an individual
interaction is minute, the rate of reactions that you see overall in your detector might actually be enough to notice.

The liquid scintillator technique provided an option for building a huge detector. The advent of nuclear technology was what provided the powerful sources of neutrinos. Heavy nuclei tend to have a higher ratio of neutrons to protons than lighter nuclei. When you split uranium in two (as happens in a nuclear bomb explosion or a nuclear reactor), the two resulting nuclei both have a lot more neutrons than they really want. So they immediately begin a series of beta decays. Nuclear explosions and sustained nuclear reactions are some of the most powerful neutrino sources we have at our disposal. Los Alamos scientist Fred Reines, who worked on the first atomic bomb tests, realized this and proposed to use the intense neutrino flux from a bomb as a neutrino source, coupled with a several-ton scintillator detector.

It is a testament to the different funding climate during those days that his proposal was awarded support by Los Alamos laboratories. In contrast to the simple, table-top Geiger-counter setup used by Chadwick, Reines and his collaborator Cowan proposed an enormous, complicated detection scheme. The initial design was actually so absurd as to be somewhat humorous. To use a bomb test as the neutrino source, you have to figure out a way to make the nearby detector immune from the physical effects of the blast. The initial proposal for Project Poltergeist (named in honor of the ghostly, elusive neutrino) involved suspending the several-ton detector on a cable that would be released at the moment of detonation, allowing the detector to operate during free-fall through a vertical shaft before falling on a bed of feathers far below. After the ambient radiation environment had subsided sufficiently, the researchers would retrieve the detector and its recorded results, hopefully finding evidence for the neutrino.

This impractical design was replaced with a much more realistic design a few years later, using a nuclear reactor as a neutrino source instead of a bomb. Using a nuclear reactor as a source for neutrinos posed some additional challenges (although none quite so daunting as how to design a detector capable of withstanding a nuclear bomb). The flux of neutrinos would be weaker, requiring the detector to be closer to the reactor and thus closer to all of the other forms of radiation also produced during the nuclear reactions in the reactor core. Scintillator detectors will produce flashes of light when any energetic charged particle or gamma ray passes through them, and nuclear reactors produce plenty of both. How, then, to disentangle the faint flashes produced by neutrino byproducts?

The main way was by using the unique temporal properties of the neutrino signature. The positron emitted from inverse beta decay will immediately annihilate with a nearby electron. Particle-antiparticle annihilations produce a pair of photons of the same energy, and each of these photons will have enough energy to knock free some electrons which will cause scintillation light in the scintillator. So, the signature of the positron will be a flash of light. Is it possible to also detect the neutron left over from the reaction? Perhaps, if the neutron is absorbed by something that also releases a radiation signal. To make sure this was possible, Reines and Cowan added Cadmium to their neutrino target (which consisted of several tanks of water between the scintillator tanks). Cadmium is an element eager to absorb neutrons, and when it does, some additional gamma rays are released. The key to this whole process is that the neutron is absorbed a little while later. So, a typical neutrino interaction will produce a flash of light in the
scintillator, followed by another one 10 microseconds later. By explicitly looking for pairs of flashes separated in time by about this amount, many of the spurious signals from ‘background’ radiation could be ignored.

This ‘delayed coincidence’ measurement technique was an important innovation. Even with this, however, Reines and Cowan faced a difficult task in convincing the world when they believed that they were seeing the first signs of the neutrino in their detector. Once again, the cross-checks and measurements of backgrounds were absolutely critical in making the case for their discovery. When they found that they were seeing ‘delayed coincidence’ signals in their detector, they needed to demonstrate that they were not ‘accidental coincidences’, where two radiation signals from other sources just happen to occur within the specified time window. Given the huge flux of radiation from the nuclear reactor, this was not easy! But, just the same way that Chadwick tested for backgrounds by ‘turning off’ the primary source of beta rays with a lead screen, Reines and Cowan could look at what happened when the nuclear reactor was turned off. Indeed, they saw the rate of coincidence signals go down (however, so did the backgrounds from the reactor). They could also change the shielding that blocked other types of radiation from the reactor. They added bags of soggy sawdust around the detector to help absorb radiation and reduce the backgrounds, and they did not see a change in the signal they were attributing to neutrinos. Finally, they changed the material inside their detector and showed that the rate of neutrino-like events changed the way they expected, assuming that they understood the underlying physics. Finally, in 1956, they announced the discovery of the neutrino. Reines later received the Nobel Prize for this work in 1995.

The story of the discovery of the continuous beta decay spectrum, the invention of the neutrino, and its eventual discovery is one of my favorite stories from the history of physics. The initial measurements of nuclear beta rays used some of the simplest radiation detectors that can be imagined. The detector used to discover the neutrino that those measurements implied was, in sharp contrast, enormous and complex: the first modern particle detector. Yet both measurements, required exceptional (for their respective eras) levels of attention to the reasoning behind their conclusions. Both incorporated, for example, cross checks like changing the detector, and careful measurements of backgrounds.

The story of beta decay and the neutrino introduces many of the topics we will cover in these lectures, including all of the subatomic physics of radioactivity and radiation processes, radiation absorption, the variety of detector technologies, the statistical nature of detection processes, and the sorts of reasoning needed to make a convincing case for a new discovery. The contrast between the extremely simple experimental setups of Chadwick’s day and the complex, multi-ton detector used by Reines and Cowan highlights how much physics we will need to learn to be able to understand the more and more subtle detection methods that physicists employ over time.
References:

*The Elusive Neutrino*, by Nicolas Solomey – This is a book that was written from a previous series of Compton lectures in 1994.

*Controversy and Consensus: Nuclear Beta Decay 1911-1934*, Aaserud, Kragh, Ruedinger, Stuewer, editors. This is a pretty technical book on early beta decay research.

*Los Alamos Science Issue 25: Celebrating the Neutrino*, Necia Grant Cooper, editor – This is a really great reference on neutrino physics up to 1997, with a mix of stories that should be accessible to non-specialists and also a lot of technical detail. You can read it online at: http://library.lanl.gov/cgi-bin/getfile?number25.htm

Lecture slides and copies of these notes will be available at:
http://kicp.uchicago.edu/~kksm/compton.html
Lecture 1 Questionnaire:

1) In a sentence or two, what would you like to get out of this lecture series?

2) If you could bring any kind of detector into this room, what kinds of radiation do you think you would be able to detect?