Introduction: trying to see the very big and the very small

Last week we took a tour of the subatomic world, by asking about the radiation emitted by objects (or human bodies) in this room. Radiation, more generally, provides the observable signals that allow us study physical phenomena, as well as the pesky backgrounds we have to avoid in order to make meaningful measurements. To learn about the nature of the fundamental particles and their interactions, we aim to detect the radiation produced when we collide particles together in accelerators. To learn about the universe, its past, and its evolution, we aim to detect radiation signals emitted from different environments across space and time. Although, sometimes new information about fundamental particles comes from studying astrophysical radiation sources, and sometimes what we learn in an accelerator has applications to the physics of distant parts of the universe. The main goal of today’s lecture is to briefly survey the radiation signals that give us information about the very small and the very large.

Much of the physics presented so far in these discussions has been treated as established fact, including the physics of the atom, nucleus, and particles. This would seem to be at odds with the premise of this series: to ask how we can know about realms of physics that are so far from our everyday experience. Yet, if we asked how every feature of the atom or the fundamental particles was discovered, we would spend all of our available time and never reach any of the exciting topics in current experimental physics. One compromise, which I will attempt today, is to mix a few historical ‘detector stories’ with a broader survey of signals of interest to current questions in physics.

Part 1: The very small

Last week, one of the questions from the audience concerned the statement that electrons and quarks are ‘pointlike’ particles. What exactly does this mean, and how is it determined? This is an excellent question for launching a discussion of how we know about fundamental particles and forces in general, and we can begin to answer it by returning to some of the same historical topics covered in the first lecture.
In 1909 Hans Geiger and Ernst Marsden (an undergraduate at the time) performed one of the first ‘scattering’ experiments using alpha particles. In a ‘scattering’ experiment, a beam of radiation of some type is aimed at a target, and we then detect the radiation after it has interacted with the target in some way. Alternatively, sometimes two beams of radiation are scattered off of each other. Perhaps the interaction is similar to what you would imagine as a collision between two billiard balls, in which particles ‘bounce’ off in different directions and at different speeds. Perhaps the interaction instead changes something fundamental about the incident radiation or the target, and what you get out is not quite the same thing as what went in. In either case, the scattered radiation can be detected and its properties carry information about the initial particles or waves, as well as their interactions.

In Geiger and Marsden’s experiment, a collimated beam of alpha particles from a radioactive source was directed at a thin platinum foil to see what would happen when alpha particles were scattered by atoms in the foil. The detector was a fluorescent screen that could be positioned at different locations around the foil. When a charged particle enters a fluorescent material (or a scintillator – fluorescence and scintillation are terms for essentially the same physical phenomenon), its electromagnetic interactions with the electrons and nuclei in the material leave many of the molecules of the material in an excited state. They then transition back to their normal state by emitting light of a particular frequency, which is in the visible range for select materials. Even though the underlying physics of fluorescent materials wasn’t necessarily understood that well in the early 1900s, fluorescent screens made a useful experimental tool because they would emit flashes of light wherever a charged particle interacted.

What Geiger and Marsden discovered was that sometimes, the alpha particles hitting the foil bounced back almost completely at 180 degrees from the direction they were initially traveling. Ernest Rutherford realized that this implied that the positive charge of the atom had to be concentrated in a dense central nucleus, because only this sort of arrangement could provide the amount of force needed to ‘back-scatter’ an alpha particle. Rutherford developed a mathematical formalism that predicted the angular distribution of scattered alpha particles (number of alpha particles scattered at a particular angle) assuming that the positive charge in the atom was concentrated, in a pointlike manner, in a nucleus. The theory was very simple, just based on the electromagnetic force between charged objects and the conservation of energy and momentum. He and others then repeated the alpha scattering experiments and carefully tested his theory. The theory held up very well – alpha particles emerged with the angular distribution you would predict if the target was a pointlike, massive positive charge.
But wait a minute – we know that we don’t think of the nucleus as a ‘pointlike’ thing. It is composed of protons and neutrons (themselves composed of quarks). These facts were also discovered through scattering experiments, but required incident radiation at higher energies. If you take an alpha particle with a low energy and propel it towards a nucleus, the nucleus will repel it and deflect the alpha particle before the alpha particle gets very close to the nucleus. If the incoming alpha particle has more energy, then it can get closer to the nucleus. It will also be deflected less than the low-energy particle. Now, imagine that the alpha particle has enough energy that it actually penetrates the nucleus. Now, suddenly, the charges that are repelling it are distributed in a diffuse cloud around the alpha particle, and the net effect is that the alpha is deflected even less than it would have been if all the nuclear charge were concentrated at a point.

This principle was applied using electron scattering on nuclei to determine that the nucleus is made up of neutrons and protons, and that these are in turn made up of quarks. If you take two protons (or a proton and an antiproton) and accelerate them to a high enough energy and collide them, you can produce quark-quark scattering. You can picture two quarks scattering off of each other in much the same way as the electron or alpha particle would scatter off of the nucleus, but the physics of the interactions is a little bit less intuitive because the strong force has some unique features. The further two quarks get from each other, the more energy they need (individual, free quarks are extremely energetically unfavorable according to how the strong interaction works). This means that as two scattered quarks travel away from each other, it is immediately favorable for them to transform their energy into additional quarks and create ‘jets’ of particles that consist of quark-antiquark pairs (mesons) or triplets (baryons). These particle jets carry the energy and momentum of the original quarks that scattered, and so their energies and angular distributions can tell us about the scattering interaction in the same way that the alpha particles or electrons scattered off of nuclei revealed the structure and interactions governing the nucleus. Such experiments have shown that quarks, like electrons, do not appear to have any substructure. It may be, however, that we have just never achieved scattering with high enough energies to probe that structure.

Let’s return, for a moment, to the question about the radiation signals that we have to detect to probe ever deeper into the nature of the fundamental particles and their interactions. To perform the scattering experiments that revealed that the atom had a dense nucleus, that this nucleus was made up of protons, and that these protons themselves were not pointlike, physicists needed to know how to detect electrons of higher and higher energies and measure their directions and energies. Nowadays, we are interested in collisions between quarks at very high energies. These collisions not only allow us to probe the structure of matter in even greater detail, but the energy in the collision also results in the production of new particles through the equivalence of mass and energy (Einstein’s famous equation).

How do you go about identifying that a new heavy particle was produced in a high-energy particle collision? Typically, the new particles are not things that we would detect directly; they would instead decay into more familiar particles (like electrons and muons, for example) that we would detect. Indirect features of the radiation from the collision have to be used to infer that the heavy particle existed for a brief moment in the detritus following a high energy event.
Whenever there are collisions of very high energy particles like those in the world’s big accelerators, many particles are created. While there are few natural backgrounds that could interfere with detecting the results of these collisions, sometimes the signature of a new heavy particle or an interesting reaction is buried in the mess of radiation departing the collision site – the rest of the radiation from the collision provides backgrounds to the measurement you are actually interested in making. As an example, suppose that a short-lived heavy particle is produced in a collision and you are hoping to obtain evidence of that particle’s existence. It travels a short distance away from the center of the collision before decaying into lighter particles. If you are able to measure the directions of all of the particles created in the whole collision process, you might be able to discover that the particles from the aforementioned decay all seem to come from a point in space that is some distance from the collision center. Similarly, you might notice that these decay products appeared a short time after the initial burst of particles. Perhaps the decay produces slightly different types of particles than the original collision did. So, in order to obtain evidence for the existence of the new heavy particle, you need to be able to discern particle type, the time that each particle interacts with your detectors, the direction it is coming from, and the energy it carries. With this information, you might be able to tell that the short-lived heavy particle was there after all.

The types of detectors that we use to study high-energy particle collisions have to be useful for all of these things. We are interested in the types, energies, directions, and timing of high energy particles produced in the collision. While the collision may produce heavy exotic particles, generally these are so short lived that we are always detecting their secondary decay products: particles ‘to the left’ on the particle chart from last week, from the first generation of fundamental particles. The most common particles produced are electrons, muons, and pions (mesons made up of up and down quarks and antiquarks). When we survey types of detectors next week, we’ll find out some of the ways we can accomplish these requirements.
Part 2: The very large

The first detectors used to explore questions about the universe as a whole were, of course, human eyes, sometimes assisted by telescopes. These got us pretty far in terms of gaining a sense of our place in the universe, but the revolution leading to modern cosmology (the science of the origins and evolution of the universe as a whole) required a little bit of technology. For much of the last century, the principal ‘detector’ used in telescopes was either a photographic film or a photographic plate, which respond to light in ways that we’ve described before and allow images of the sky to be recorded. The extra bit of ‘detector technology’ that helped usher in the era of modern cosmology was the spectrograph, a device for splitting visible light into its constituent colors. A simple prism will accomplish this, splitting the light into different colors based on the fact that the index of refraction of the prism material varies for light of different frequencies.

In the 1920s, Edwin Hubble and Milton Humason and others used spectrographs to photograph the spectra of a large number of galaxies. Hubble and Humason took a collection of these galaxies and measured the distance to each galaxy using the apparent brightness and the pulsation period of variable stars called Cepheids. These stars oscillate from bright to dim over some period of time, but their maximum brightness has a more-or-less fixed relationship to the oscillation period. This makes them useful ‘standard candles’ for measuring astrophysical distances. If a Cepheid is identified in a distant galaxy and its period of oscillation is measured, then you know how bright it actually is. If it appears dim, then this implies that the galaxy is at a great distance. This technique for measuring the distances to galaxies was imperfect, but worked well enough for Hubble to rank the galaxies according to their distance from us.

We’ve discussed before how, because of the quantum mechanical nature of atoms, different species of atom will absorb and emit light of specific frequencies or wavelengths. One of the most prominent spectral features in galaxies like those in Hubble’s sample is a pair of ‘absorption lines’ associated with the atomic spectrum of calcium. That is to say, there are two close-spaced frequencies at which calcium absorbs light, and the presence of calcium in the stars therefore leads a pair of ‘gaps’ in the spectrum of galaxy light at those frequencies.
The critical observation that Hubble made was that the characteristic pair of lines associated with calcium actually appeared at different places in the measured spectra, and they appeared more towards the red end of the spectrum for galaxies that were further away. This ‘red shift’ could be caused by relative motion in which the galaxies were receding from us, with the distant galaxies receding faster. When an object that emits light is moving away from us, the light from that object appears to be stretched out to a longer wavelength, making it ‘redder’, and the speed of that object determines how much reddening takes place. This phenomenon is called ‘Doppler shifting’ and also occurs for sound waves.

Hubble’s observation that more distant galaxies appeared to be moving away from us at higher speeds had dramatic implications if the redshifts were interpreted as Doppler shifts in this way. First of all, the universe could no longer be assumed to be a static place. The most straightforward interpretation of Hubble’s observations is that the universe is expanding. This is a profound conclusion to have reached from some relatively simple measurements of the brightness and spectra of galaxy light! Nowadays, we actually do not view the redshifts of distant objects as being strictly ‘Doppler shifts’, because we do not view those objects as moving at some great velocity through space relative to us. Instead, we believe that
the space in between us and those distant objects has expanded itself, stretching out the wavelengths of light to make it redder. Either way you look at it, you end up invoking some sort of expansion to explain Hubble’s results, and the subtleties should not obscure the profound implications of his discovery: not only is the universe not a static place, but the evidence for expansion implies that the matter in today’s galaxies and stars was once compressed into a much smaller volume of space.

The ‘big bang’ theory takes this idea to its logical conclusion, postulating that all of the matter in the universe was once compressed into an unimaginably small space. The major predictions of the big bang theory have now been tested very well, with the most important of these being the presence of a cosmological ‘background’ radiation. With our basic understanding of radiation physics we can understand why such radiation should occur.

If you compress matter into a smaller space, it tends to heat up to the point that neutral atoms can no longer exist, because there is so much energy being exchanged between the particles (through the emission and absorption of photons) that all of the atoms are ionized. If you imagine that the universe was much smaller early in its history, there must have been a point when all of matter was just a hot ionized gas, before the universe expanded and cooled enough that atoms could form. While everything was in this hot gas, a lot of energy was being exchanged in the form of photons at all frequencies, in exactly the same kind of thermal black-body spectrum we discussed last week. However, as soon as atoms began to form, much of this photon radiation was no longer re-absorbed by the matter in the universe, and it was free to stream into space unimpeded.

According to the big bang, then, everywhere we look we should see a cosmological background of photons that are left over from the early universe. These photons should have a very perfect black-body spectrum, because they represent the thermal radiation from a hot ionized gas early in the universe. They are arriving at the earth from a very great distance, and like the photons arriving from more distant galaxies, we expect that they’ve been redshifted. Although they originally started out as thermal radiation with a peak quite high in the electromagnetic spectrum, we should observe them now in the low-energy, microwave region of the spectrum.

The big bang model predicts that such radiation should exist, and when Penzias and Wilson of Bell Labs finally discovered it in the early 1960s, their discovery was hailed by physicists as an extremely compelling
evidence that the theory is correct. Penzias and Wilson were working with a large horn antenna that was previously employed as part of a radio signaling system, for bouncing radio waves off of balloons high in the atmosphere. They were interested in using the antenna as a radio telescope to look at objects in the cosmos that emit radio waves, but they were impeded by an unexpected background signal in their measurements. They tried to figure out the source of this background, but could not attribute it to any local radiation sources, instrument problems, or specific sources on the sky. The radiation signal was always there, coming from all directions. They were able to measure the intensity of the signal from their telescope. By assuming that the radiation came from a thermal black-body of some sort, they could infer the temperature, which came out to be about 3K. This was exactly the sort of ‘Cosmic Background Radiation’, or (‘Cosmic Microwave Background’, since the peak of the 3K thermal spectrum is in the microwave) that the big bang predicted.

So let’s come back to the question of what sorts of radiation you need to detect to further probe the evolution of the universe and test the big bang model. Clearly, close investigation of the CMB is critical in all of this, because it gives us a direct record of conditions at a much earlier point in the history of the universe. So, we need ways to detect microwaves that are coming from space. I mentioned last week that this can be challenging on the earth, because the thermal radiation of just about everything around us is stronger than the signal we are hoping to see.

Besides the CMB, the main way that we learn about the evolution of the universe is by looking at how matter has clumped together over time to form the structures like galaxies and clusters of galaxies that now exist in the universe around us. Because light moves at a finite speed, if something is far away from us, it takes longer for the light to reach us. Therefore, looking further away in space means we are actually looking back in time, and seeing objects as they were when the light was emitted. This lets us directly test how classes of objects in the universe have evolved under the influence of things like dark matter and dark energy (about which there will be more to come in these lectures). The critical thing that we need for these sorts of studies is to know where an object is in space, and how far away it is from us. Electromagnetic radiation is our best way to do this. Electromagnetic radiation is emitted anywhere that there is a concentration of ordinary matter, and it manages to reach us without being deflected by magnetic fields that can skew the paths of particle radiation from space, so we can accurately determine the location of its source. By measuring the spectrum of electromagnetic radiation from a particular object, we can get a handle on the distance to that source. Often we use visible light for probes of the structure and evolution of matter in the universe, but sometimes we use electromagnetic radiation in other portions of the spectrum such as x-rays, which are emitted by hot clouds of gas in places like the centers of clusters of galaxies.

To answer questions about the realm of the very large, then, the main thing we need is detectors to detect electromagnetic radiation from relatively low energies (microwaves) to high energies (x-rays). Especially for light in the optical region of the spectrum, we need ways to measure spectra. No matter what form of electromagnetic radiation we are detecting, it is most valuable if we know the direction it is coming from to as high an accuracy as possible, so that is also something that figures into telescope and detector design.
Part 3: Some of the things that don’t fit

To probe the structure of matter and the interactions in the Standard Model with accelerators, we need particle detectors that can detect the high-energy charged particles resulting from particle collisions. To study the big bang and trace the evolution of the universe as a whole, we need a range of detectors tailored to electromagnetic radiation at different energies. There are a number of significant open questions in physics that do not quite fit cleanly into either of these categories. I am just going to pick two to emphasize some additional interesting radiation and detection issues.

For the questions discussed so far about the very small and the very large, the radiation signals to seek have primarily been electrically charged particles or light of some form. Both can be fairly easily directly detected because photons and charged particles will interact through the electromagnetic force as they pass through matter, in ways that can be amplified and recorded. However, there are some forms of interesting radiation that do not interact through the electromagnetic force. Two of these that are important to current-day physics are neutrinos and the postulated dark matter particles.

The way to detect neutrinos (and the way suggested for detecting dark matter particles, if they exist) is to wait for these particles to interact via the weak interaction in matter. Depending on the nature of the interaction, perhaps secondary charged particle radiation or light is produced (some dark matter detection techniques also use ways of detecting tiny vibrations in a crystal lattice that are caused by the weak interactions of dark matter particles in the detectors). If secondary charged particles or light are produced, you can use similar detector technologies to those used elsewhere. However, for dark matter particles and many interesting neutrino questions, a significant difference is that the secondary radiation produced is lower in energy than many of the other interesting signals we deal with in experimental physics. Perhaps the biggest consequence of this is that these measurements are susceptible to debilitating background radiation from ordinary processes like the radioactivity present in all ordinary materials.

Beginning next week, we will describe some of the principle detector technologies that are used for detecting electromagnetic radiation and charged particles at many energies. We will pay particular attention to the features these detectors have to have to be useful for answering questions about the very big and the very small.

A few references:

For rigorously understanding Rutherford scattering, the best place to look is probably any so-called ‘Modern Physics’ textbook. My favorite is Modern Physics, from alpha to Z0 by James William Rohlf. The hyperphysics web site also has some very handy graphics and conceptual explanations about scattering (coupled with all of the actual equations), at:
http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/scatsurv.html

I have not found what I think is a really good detailed (but non-technical) discussion of particle accelerators and particle collisions, but if I find a good general reference I will point it out. For the time being, the Particle Adventure site has a lot of fun particle physics topics: http://particleadventure.org/

An interesting article reflecting on Hubble’s original distance-redshift observations can be found at: http://www.pnas.org/cgi/content/full/101/1/8

A reasonable first place to go to get a feel for the major concepts in cosmology is the NASA/WMAP public outreach webpage at: http://map.gsfc.nasa.gov/universe/