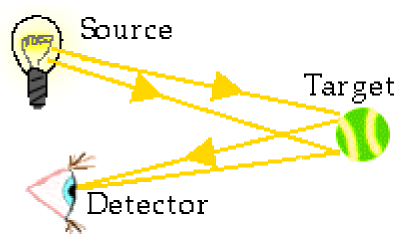
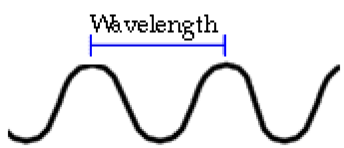
How do scientists “see” inside the atomic nucleus?

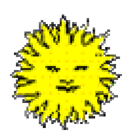
Well, how do you see anything?

Light (particles called photons) bounces off of objects and into your eyes. You are a photon detector! You can detect how many photons there are (how bright). You can tell by the different photon wavelengths what color an object is. Your brain (computer) analyzes the photon detector (eye) information, and creates the sense of a “tennis ball” or “poster” in your mind.



Our personal detectors, the eyes, are attuned to visible light, which has wavelengths in the neighborhood of 0.0000005 meters. That’s not small enough to analyze anything smaller than a human cell.



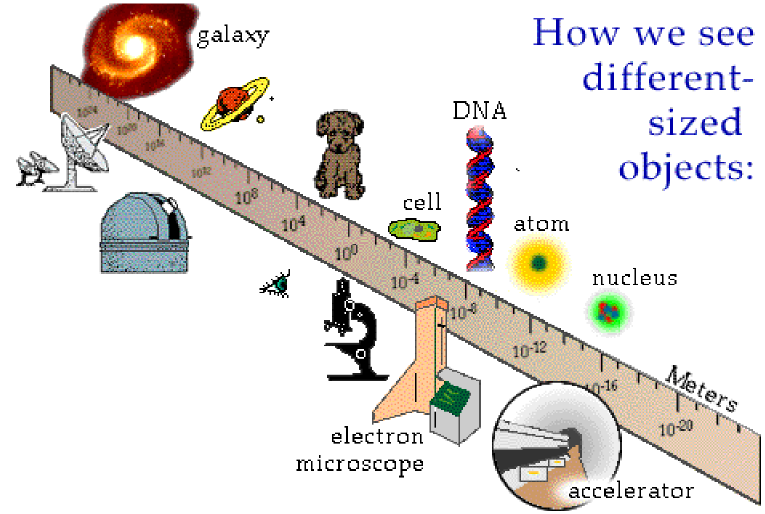


Symbol for wavelength is λ

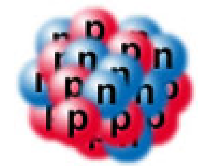
To observe things under higher magnification, you must use waves with smaller wavelengths. That’s why people turn to electron scanning microscopes when studying sub-microscopic things like viruses. However, even the best scanning electron microscope can only show a fuzzy picture of an atom.

Jefferson Lab is a kind of giant microscope for the subatomic world.

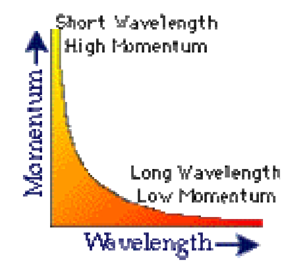
How we see different-sized objects:



At Jefferson Lab, we want to look inside the atomic nucleus, where protons and neutrons reside, and even inside these protons and neutrons themselves, the realm of quarks and gluons. Since the atomic nucleus has a diameter roughly one-thousandth that of an atom, physicists need a particle with the shortest possible wavelength.



To do this, physicists use the principle that a particle’s energy and its wavelength are inversely related. This means, “the higher the energy, the shorter the wavelength.”



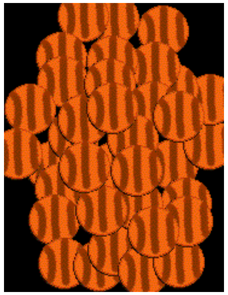
We apply this principle when using our electron accelerator to increase the electron’s momentum, speeding it up to very nearly the speed of light, and then slamming these probing electrons into the target and record what happens. Since the electrons have a lot of momentum, their wave lengths are small and we can see far inside the atomic nucleus.

Yeeeeeeehaaaaaaaa!! 

How do we detect what is happening?

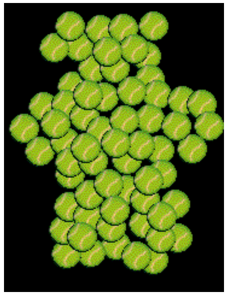
Pretend that Joe is in a dark cave without a flashlight. However, Joe did bring a large bag of glow-in-the-dark basketballs. Suddenly, Joe hears a snuffling sound.

To make sure what it is, Joe desperately tosses the basketballs in the direction of the sound, and memorizes where the basketballs hit. Thus, he figures out the outline of the being in front of him:



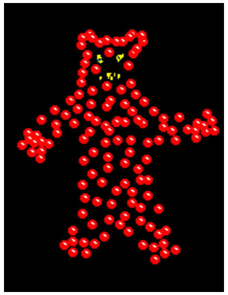
Yikes, since Joe's basketballs are so big, when they bounce off the thing in front of him, all he can learn about its shape is that it is wide and tall.

Brad ended up in the same situation, but brought a bucket of glow-in-the-dark tennis balls. He again tosses them in the direction of the snuffling sound, and is rewarded with the following image:



Hmm…. Not much better. Tennis balls are still too big to figure out the shape of the object they hit. Brad only has a rough outline about the thing's outline.

Sally luckily brought a bag of glow-in-the-dark marbles. She tosses these little balls at the being, and can figure out a pretty clear image of the thing's shape. It seems to be big, hunched over, and have enormous claws. She runs away!

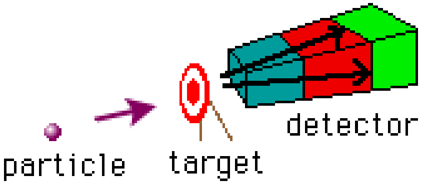


Clearly, the smallest possible probe allows you to get the most information about your fate!

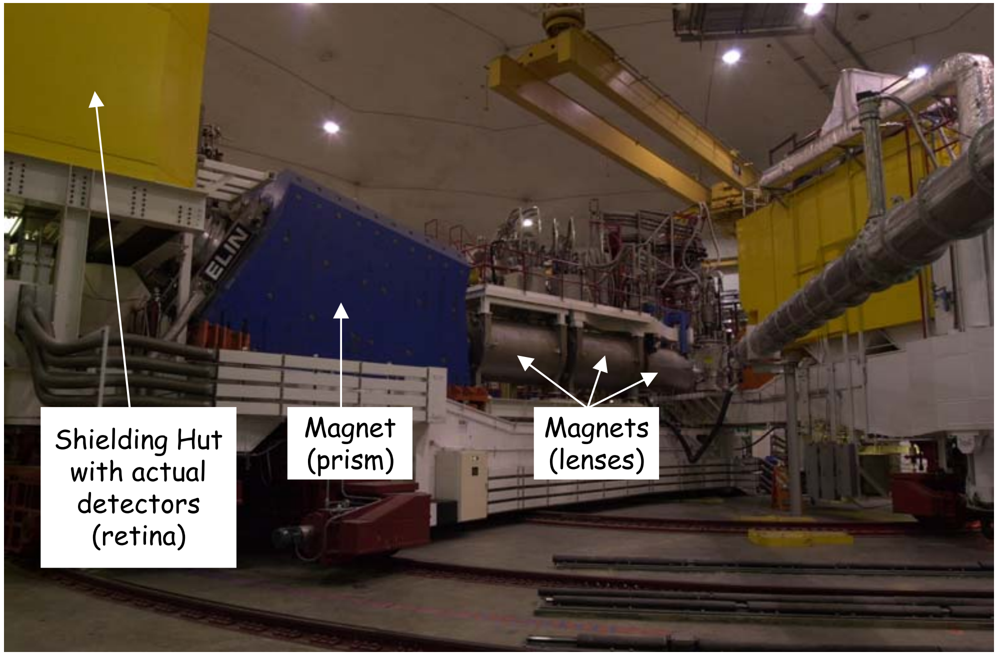
How do we experiment with tiny particles?

In the experiments at Jefferson Lab, we accelerate electrons to nearly the speed of light, and then collide them with a "fixed" target that can be a solid, liquid, or gas.

Physicists are curious about the events that occur during and after a particle's collision. For this reason, they place detectors in the regions where they expect the electrons to scatter or particles to be produced. For the fixed-target experiments at Jefferson Lab, the particles generally fly in the forward direction.



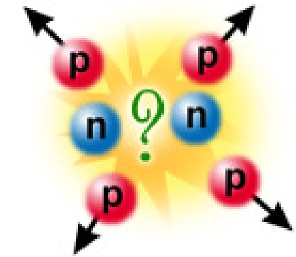
In Hall C at Jefferson Lab, we often use "magnetic spectrometers" for our experiments. Such a magnetic spectrometer works just as your eye, and consists of magnets that focus the scattered electrons or the produced particles, and analyze their momentum (or wavelength). Finally, the electrons or particles are recorded in the actual detectors (a similar camera as your retina) that live in a well-shielded area to protect them from particles that have nothing to do with the event (background events). Lastly, the signals are sent to computers that just like your brain interpret what happened.



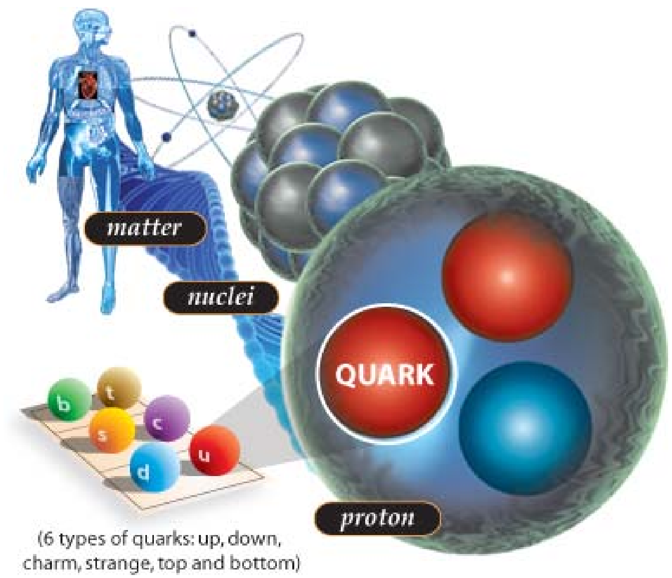
Jefferson Lab's spectrometers are giant eyeballs into the sub-atomic world.

The atomic nucleus, quarks and gluons

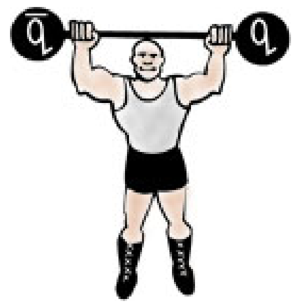
The atomic nucleus occupies one-trillionth the volume of an atom and is a bunch of protons and neutrons crammed together. Since neutrons have no charge and the positively-charged protons repel one another, **why doesn't the nucleus blow apart?**



We cannot account for the nucleus staying together with just the electromagnetic force (the force between charged particles). What else could there be? Gravity? Nope! The gravitational force is far too weak to overpower the electromagnetic force….
To understand what is happening inside the atomic nucleus, we need to understand more about the **quarks** that make up the protons and neutrons in the nucleus. Quarks have electromagnetic charge, and they also have an altogether different kind of charge called **color charge**. The force between color-charged particles is very strong, so this force is "creatively" called Strong



The strong force holds quarks together to form protons and neutrons, so its carrier particles are whimsically called **gluons** because they so tightly "glue" quarks together.

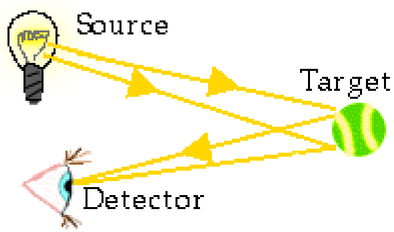


While quarks (and gluons!) have color charge, composite particles made out of quarks have **no net color charge**. For this reason, the strong force only takes place at the really small level of quarks, which is why you are not aware of the strong force in your everyday life! Still, the gluons manage to "glue" the atomic nucleus together! You can think of an atomic nucleus as a tightly coiled spring which is the electrical repulsion. held in place by a very big rope. There is a lot of stored energy in the system, yet it can't be released because the rope is too strong.

Did you know that:
- You can never find one quark by itself?
- Protons and neutrons comprise most of the visible mass around you?
- Most of your mass is due to the stored energy of the quarks locked up into protons and neutrons?
- Quarks move with nearly the speed of light, and protons with about one-fourth the speed of light inside your body?

How do scientists "see" inside the atomic nucleus?

Imagine there is a light bulb behind you, and a tennis ball in front of you. Photons travel from the light bulb (source), bounce off the tennis ball (target), and when these photons hit your eye (detector), you infer from the direction the photons came from that there is a round object in front of you. Moreover, you can tell by the different wavelengths that the object is green/tan. Our brain (computer) analyzes the information, and creates the sense of a "tennis ball" in our mind.



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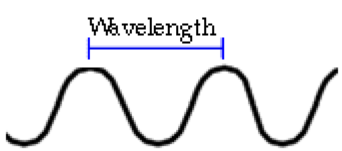

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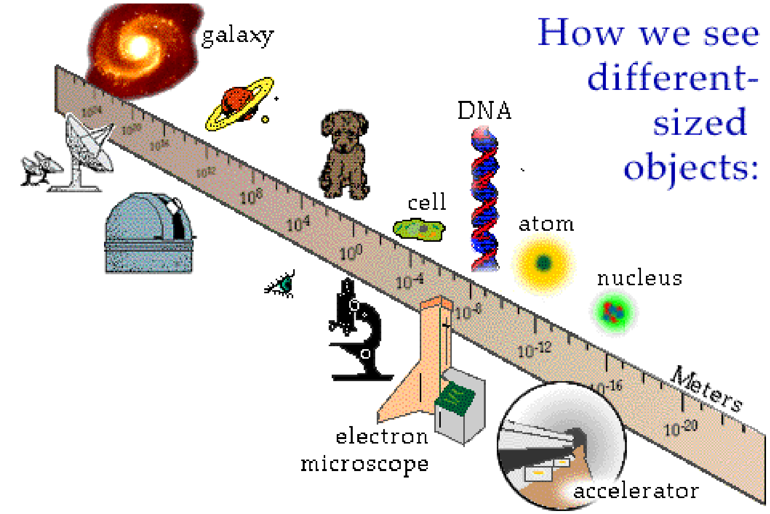

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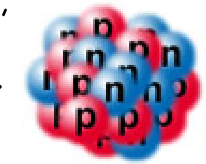
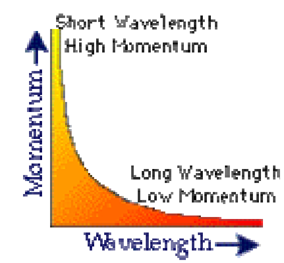


In order to "see" the smallest details, physicists need a particle with the shortest wavelength possible. They use the principle that a particle's momentum and its wavelength are inversely related.



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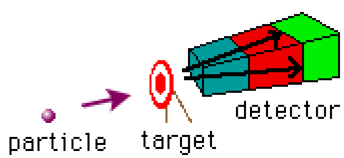

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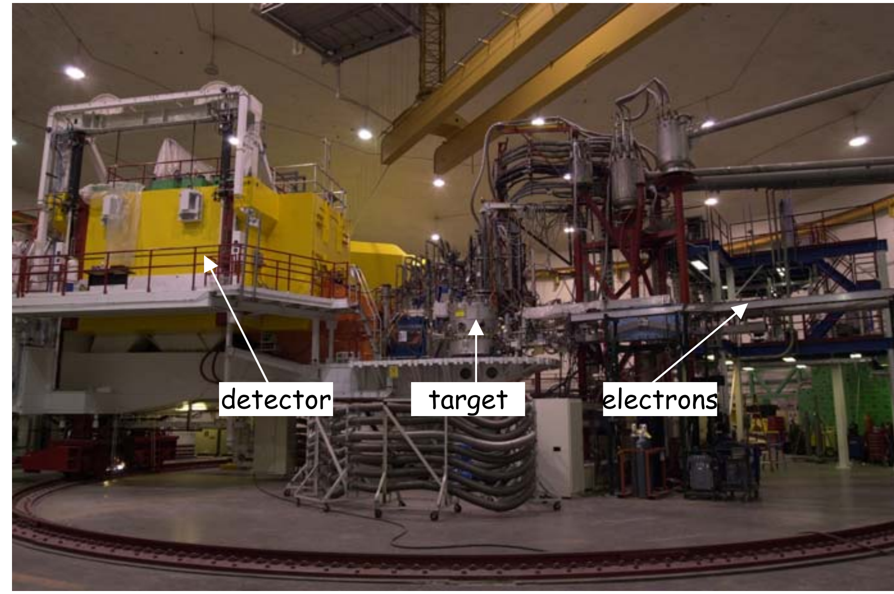

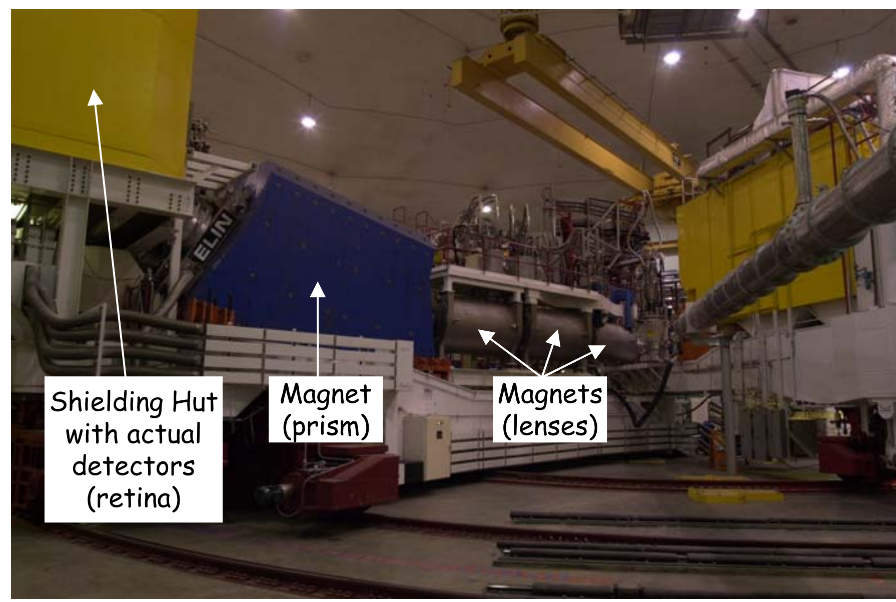

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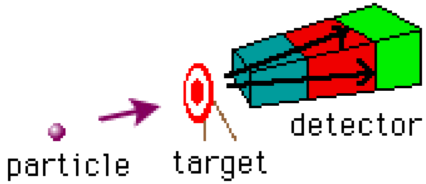

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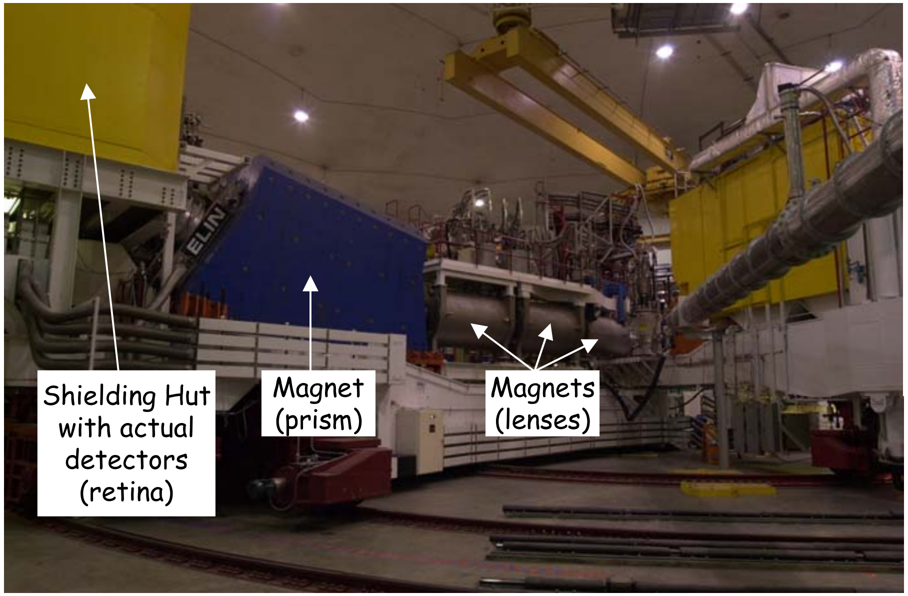

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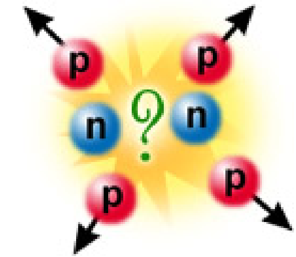

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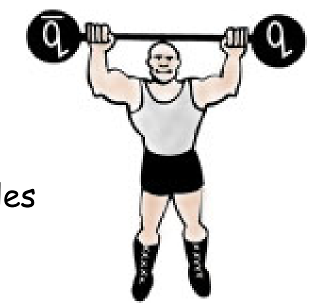

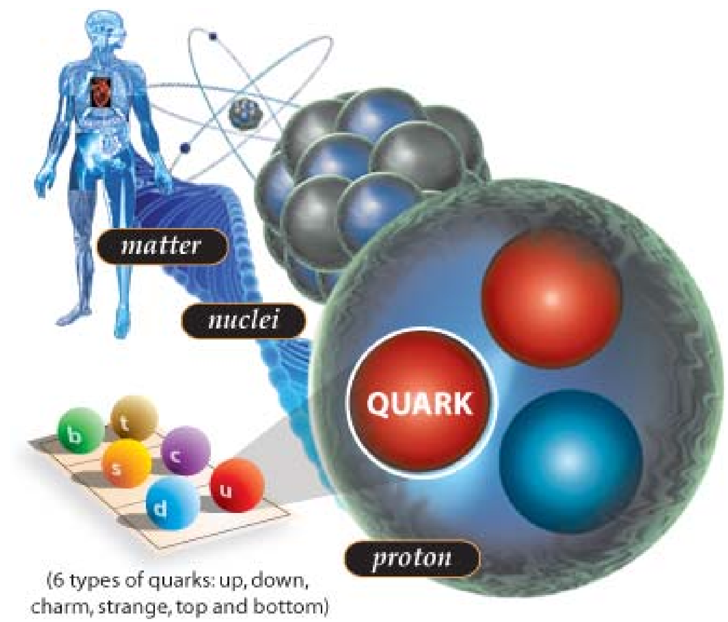

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