Particle Accelerators

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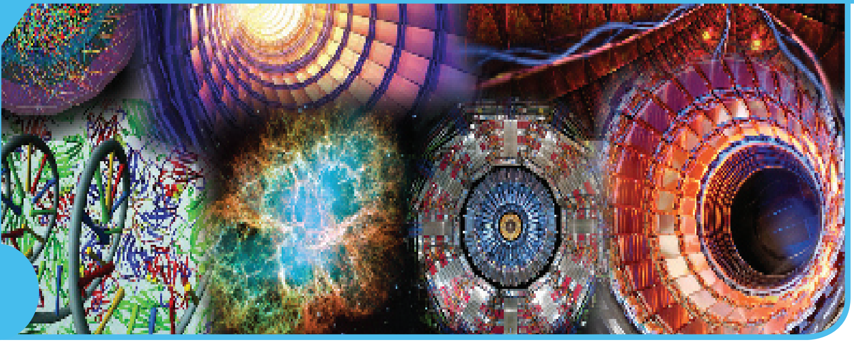
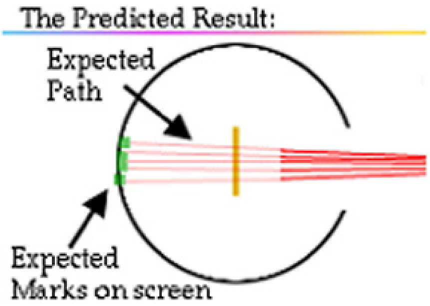


In 1909, the prevailing theory of the atom's structure was that atoms were mushy, semi- permeable balls. So in 1909 a man named Ernest Rutherford set up an experiment to test the validity of the prevailing theory. In doing so he established a way for the first time where physicists could "look into" tiny particles they could not otherwise see with microscopes.

In Rutherford's experiment, a radioactive source shot a stream of alpha particles at a sheet of very thin gold foil which stood in front of a screen. The alpha particles would make little flashes of light where they hit the screen.

The alpha particles were expected to pass right through the very thin gold foil and make their marks in a small cluster on the screen.

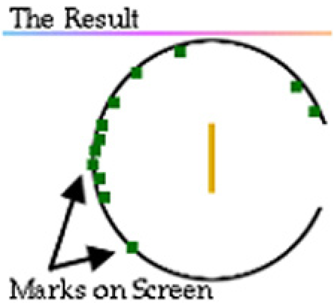
If atoms were permeables neutral balls, then the alpha particles should simply pass through the gold foil and strike the back of the screen. But much to everyone's surprise, some of the alpha particles were deflected at large angles to the foil; some even hit the screen in front of the foil! Obviously some other explanation was needed.

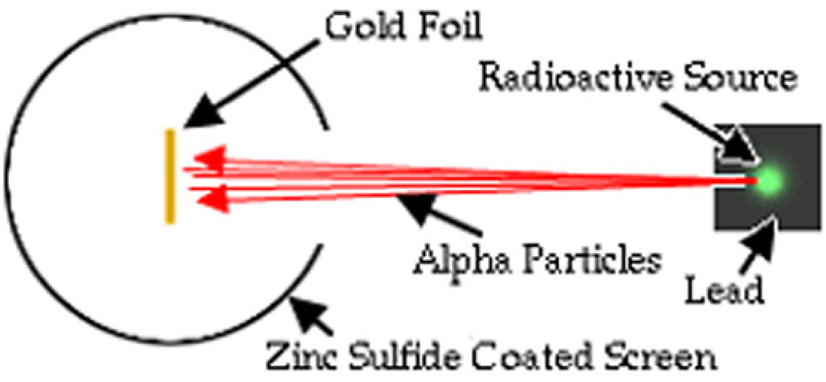


Since some of the positive alpha particles were substantially deflected, Rutherford concluded that there must be something inside an atom for the alpha particles to bounce off of, that is, small, dense, and positively charged: the nucleus. Rutherford's experiment set the tone for the realm of experimentation in particle physics. In fact, almost all particle physics experiments today use the same basic elements that Rutherford did:

- A beam (in this case, the alpha particles)
- A target (the gold atoms in the foil)
- A detector (the zinc sulfide screen)

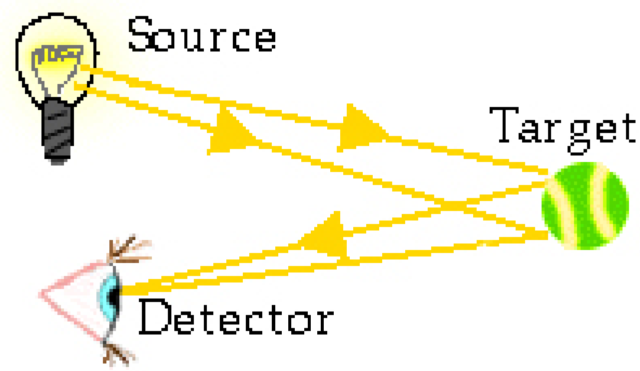
In addition, Rutherford established the practice of "seeing" into the sub-atomic realm by using particle beams, and particle physicists today follow his experimental lead by inferring the actual nature of particles and interactions from the frequently counterintuitive results they find.





Let us look at the most familiar example of this source/target/detection scheme: the way in which we perceive the world.

Imagine that 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

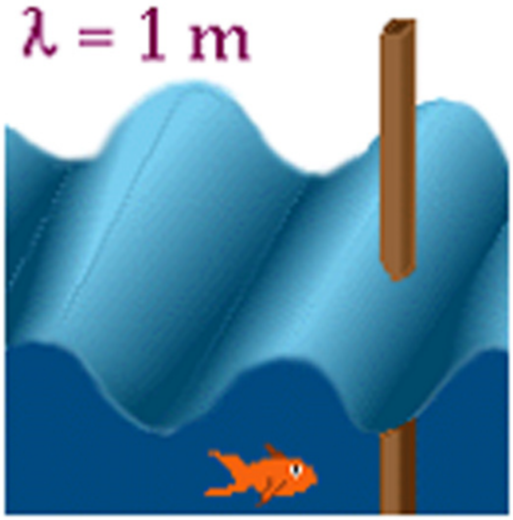


direction the photons came from that there is a round object in front of you. Moreover, you can tell by the different photon wavelengths that the object is green and tan. Our brain analyzes the information, and creates the sense of a "tennis ball" in our minds, and this mental model of the tennis ball helps us to describe the reality around us.

We use the information of bounced-around light waves to perceive our world. Other animals, like dolphins and bats, emit and detect sound waves. In fact, any kind of reflected wave can be used to get information about the surroundings.

The problem with using waves to detect the physical world is that the quality of the image is limited by the wavelength that is used.

Our eyes are tuned to visible light, which has wavelengths in the neighborhood of 0.0000005 meters. That is small enough that we usually do not need to worry about the wavelength-resolution problem since we do not look at things that are 0.0000005 meters wide.



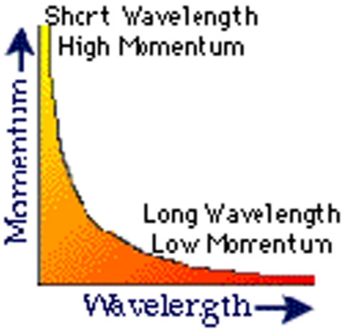
However, the wavelength of visible light is too wide to analyze anything smaller than a cell. To observe things under higher magnification, you must use waves with smaller wavelengths. That is why people turn to scanning electron microscopes when studying sub-microscopic things like viruses. However, even the best scanning electron microscope can only show a fuzzy picture of an atom.

Things with long wavelengths cannot provide too much detail about what they hit. Things with short wavelengths can provide you with fairly detailed information about what they hit. The shorter the probe's wavelength is, the more information you can get about the target.

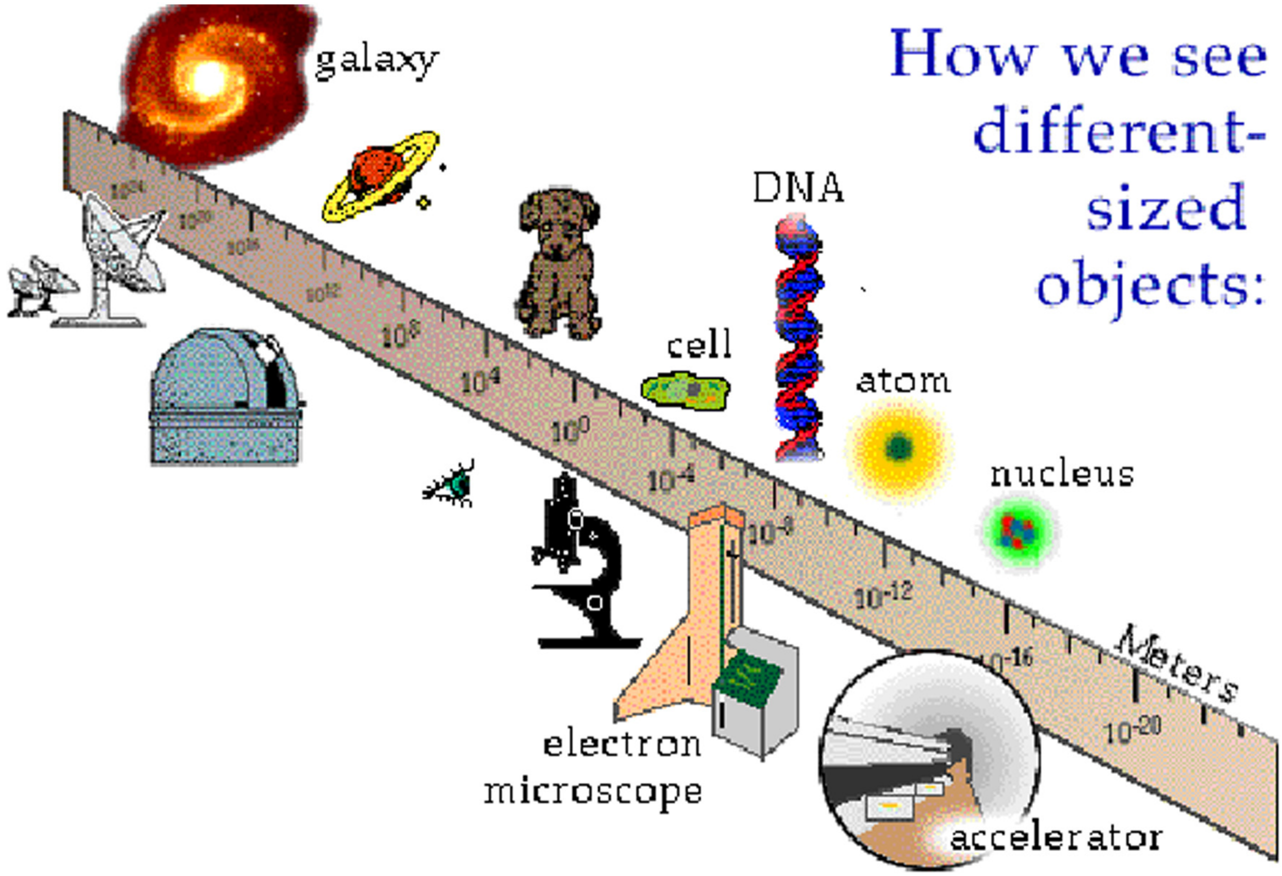
A good example of the wavelength vs. resolution issue is a swimming pool. If you have a swimming pool with waves which are 1 meter apart (a 1 meter wavelength) and push a stick into the water, the pool's waves just pass around the stick because the 1 meter wavelength means that the pool's waves would not be affected by such a tiny target.

All particles have wave properties. So, when using a particle as a probe, we need to use particles with short wavelengths to get detailed information about small things. As a rough rule of thumb, a particle can only probe down to distances equal to the particle's wavelength. To probe down to smaller scales, the probe's wavelength has to be made smaller.

Physicists can not use light to explore atomic and sub-atomic structures because light's wavelength is too long. However, since ALL particles have wave properties, physicists can use particles as their probes. In order to see the smallest particles, physicists need a particle with the shortest possible wavelength. However, most of the particles around us in the natural world have fairly long wavelengths. How do physicists decrease a particle's wavelength so that it can be used as a probe?



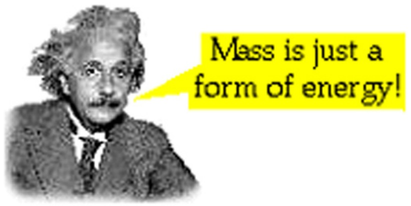
A particle's momentum (p) and its



wavelengths are inversely related. In fact , where h is the Planck constant.

High-energy physicists apply this principle when they use particle accelerators to increase the momentum of a probing particle, thus decreasing its wavelength. The steps followed by particle Physicist's are,

- Put your probing particle into an accelerator.
- Give your particle lots of momentum by speeding it up to very nearly the speed of light.
- Since the particle now has a lot of momentum, its wavelength is very short.



- Slam this probing particle into the target and record what happens.

The above image represents a meter stick measuring powers of ten. As you can see, there are different methods to view the world corresponding to the size of the thing you are viewing.

- Accelerators solve two problems for physicists. Firstly, physicists use accelerators to increase a particle's momentum, thereby decreasing its wavelength sufficiantly that it could be pushed inside atoms. Secondly, the energy of speedy particles is used to create massive particles that physicists want to study.
- Quite often, physicists want to study massive, unstable particles. However, all that physicists have around them are very low-mass particles. How does one perform this amazing feat of using particles with lesser mass to obtain particles of greater mass?

- You know Albert Einstein's famous equation where E is the energy, m is the mass, and c is the speed of light.
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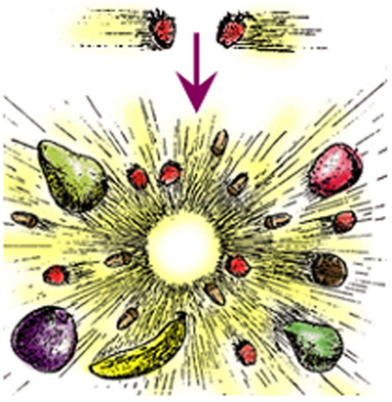
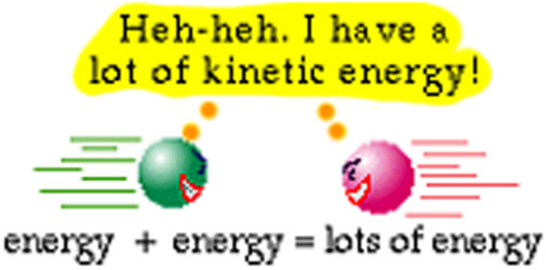
- When physicists want to





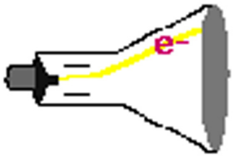
use particles with low mass to produce particles with greater mass, all they have to do is put the low-mass particles into an accelerator, give them a lot of kinetic energy (speed), and then collide them together. During this collision, the particle's kinetic energy is converted into the formation of new massive particles. It is through this process that we can create massive unstable particles and study their properties.

How do accelerators work?

- Basically, an accelerator takes a particle, speeds it up using electric fields, and bashes the particle into a target or other particles.

How do physicists get the particles they want to accelerate?

- Electrons: Heating a metal causes electrons to be ejected. A television, like a cathode ray tube, uses this mechanism
- Protons: They can easily be obtained by ionizing hydrogen



There are several different ways to design these accelerators, each with its benefits and drawbacks. Here is a quick list of the major accelerator design choices:

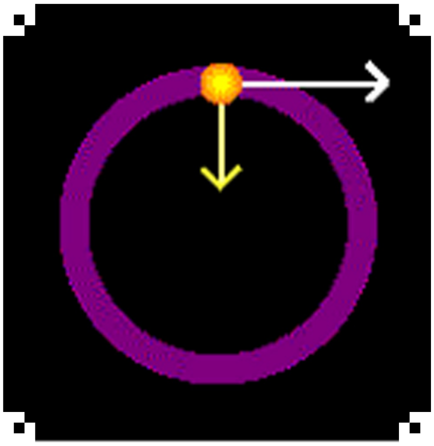
Fixed target: In a fixed-target experiment, a charged particle such as an electron or a proton is accelerated by an electric field and collides with a target, which can be a solid, liquid, or gas.

Colliding beams: In a colliding-beam experiment two beams of high-energy particles are made to cross each other.

- The advantage of this arrangement is that both beams have significant kinetic energy, so a collision between them is more likely to produce a higher mass particle than would a fixed-target collision (with the one beam) at the same energy. Since we are dealing with particles with a lot of momentum, these particles have short wavelengths and make excellent probes

Accelerators are shaped in one of two ways:

- Linacs: Linear accelerators, in which the particle starts at one end and comes out the other.



- Cyclotrons: Accelerators built in a circle, in which the particles go around and around and around.

All accelerators are either linear or circular, the difference being whether the particle is shot like a bullet from a gun (the linear accelerator) or whether the particle is twirled in a very fast circle, receiving a bunch of little kicks each time around (the circular accelerator). Both types accelerate particles by pushing them with an electric-field.

The particles in a circular accelerator go around in circles because large magnets tweak the particle's path enough to keep it in the accelerator. How do a circular accelerator's magnets make particles go in a circle?

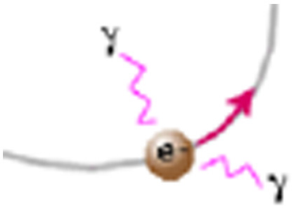
To keep any object going in a circle, there needs to be a constant force on that object towards the center of the circle. In a circular accelerator, an electric field makes the charged particle accelerate,

while large magnets provide the necessary inward force to bend the particle's path in a circle. (In the image shown, the particle's velocity is represented by the tangential arrow, while the inward force supplied by the magnet is shown by the arrow directed towards the center)

The presence of a magnetic field does not add or subtract energy from the particles. The magnetic field only bends the particles' paths along the arc of the accelerator. Magnets are also used to direct charged particle beams toward targets and to "focus" the beams, just as optical lenses focus light.

The advantage of a circular accelerator over a linear accelerator is that the particles in a circular accelerator go around many times, getting multiple kicks of energy each time around. Therefore, synchrotrons can provide very high-energy particles without having to be of tremendous length. Moreover, the fact that the particles go around many times means that there are many chances for collisions at those places where particle beams are made to cross.

On the other hand, linear accelerators are much easier to build than circular accelerators because they do not need the large magnets required to guide particles into going in a circle. Circular accelerators also need an enormous radii in order to get particles to high enough energies, so they are expensive to build. Another thing that physicists need to consider is that when a charged particle is accelerated, it radiates away energy. At high energies the radiation loss is larger for circular acceleration than for linear acceleration. In addition, the radiation loss is much worse for accelerating light electrons than for heavier protons. Electrons and anti-electrons (positrons) can be brought to high energies only in linear accelerators or in circular ones with large radii.



We invite you to explore the basic plans of the world's major accelerators so that you can truly appreciate the differences in accelerator designs.

SLAC: Stanford Linear Accelerator Center, in California, discovered the charm quark (also discovered at Brookhaven) and tau lepton; now running an accelerator producing huge numbers of B mesons.

Fermilab: Fermi National Laboratory Accelerator, in Illinois, where the bottom and top quarks and the tau neutrino were discovered.

CERN: European Laboratory for Particle Physics, crossing the Swiss-French border, where the W and Z particles were discovered.

BNL: Brookhaven National Lab, in New York, simultaneously with SLAC discovered the charm quark.

CESR: Cornell Electron-Positron Storage Ring, in New York. CESR performs detailed studies of the bottom quark.

DESY: Deutsches Elektronen-Synchrotron, in Germany; gluons were discovered here.

KEK: High Energy Accelerator Research Organization, in Japan, is now running an accelerator producing huge numbers of B mesons.

IHEP: Institute for High-Energy Physics, in the People's Republic of China, performs detailed studies of the tau lepton and charm quark.

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