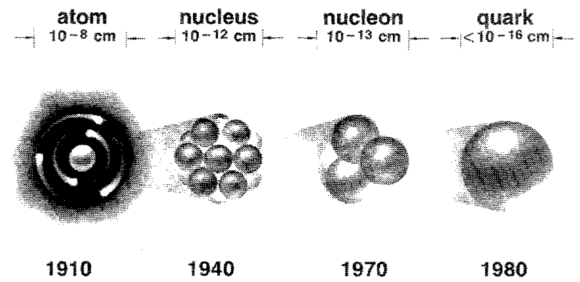

Figure 1. Atoms are known to be composed of electrons and nuclei, which are themselves made of protons and neutrons. These nucleons, in turn, are built of quarks.

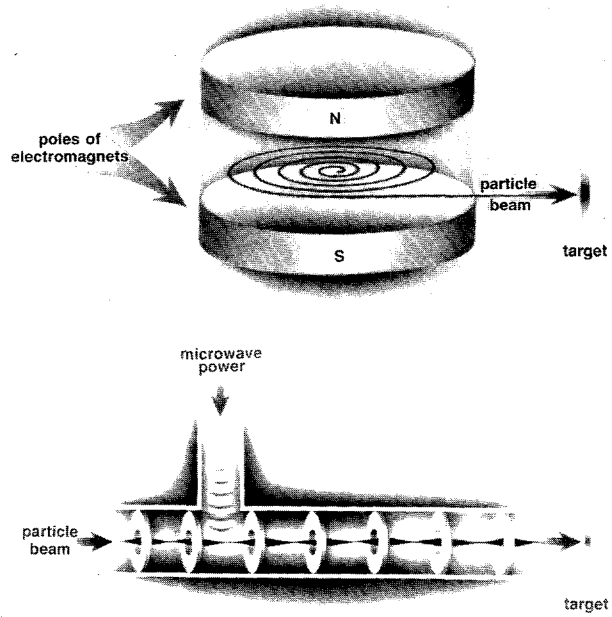

Figure 2. Simplified sketches of a cyclotron and a linear accelerator.

When Rutherford and collaborators later resolved nuclei into protons and neutrons, physicists naturally wanted to take a closer look at them, too. But to do so required even higher energies. Projectiles with enough energy could be found in the hail of naturally occurring cosmic rays raining down from the heavens. But they provided a chaotic, unreliable source at best—hardly conducive to systematic studies. Exotic new particles often turned up in this celestial debris, but it was difficult to learn much about their innate properties and proclivities.

Thus was born the need for modern particle accelerators. These devices subject particles with electric charges, like the proton and electron, to intense electric and magnetic fields that push on them relentlessly. The particles gain energy in transit and emerge in compact beams or bunches. Circular machines called *cyclotrons,* able to accelerate protons to tens of millions of volts, were developed during the 1930's by a group of physicists at the University of California, Berkeley, led by Ernest Lawrence. In the late 1940's *linear accelerators* were built at Stanford University that could propel electrons to similar energies. Shortly after World War II, protons and then electrons were accelerated to hundreds of millions of volts—enough energy, in fact, to begin producing new particles in the laboratory.

Physicists measure the energy imparted to a subatomic particle in units of *electron volts*. One electron volt, written 1 eV, is just the energy an electron picks up as it falls through a potential drop of one volt. This is about the energy an electron gains in traversing an ordinary flashlight battery. The streams of electrons in a common television set pass through a potential drop of thousands of volts before striking the phosphor screen to produce images. Thus they gain energies of thousands of electron volts—or keV, in physicists' shorthand. Similar amounts of energy are imparted to the electrons in an electron microscope.

Accelerators of the 1930's and 1940's generated particles with energies in millions of electron volts, written MeV. Today's accelerators do much better. Electrons and protons emerge with energies measured in billions or even trillions of electron volts (written GeV and TeV, respectively). The Stanford Linear Accelerator, for example, speeds electrons to energies of 50 GeV, or 50,000 MeV. The Tevatron at the Fermi National Accelerator Laboratory accelerates protons to almost 1 TeV, or 1,000 GeV.

According to Albert Einstein's famous equation, $E = mc^2$, one can convert energy into an equivalent amount of mass, and vice-versa. Thus we can express the mass of a subatomic particle in terms of equivalent energy units—the total amount of energy locked up in its mass. The electron has a mass-energy of 511 keV or 0.511 MeV, for example, while the proton and neutron weigh in at 938 and 940 MeV, or almost 1 GeV. This may sound like a lot of energy, and it is, on a subatomic scale. But it only corresponds to a mass of about a trillionth of a trillionth of a gram!