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Particle Accelerators: Their Triumphant History and Uncertain Future

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The history of particle physics can be considered nothing less than a huge triumph for science. Over the course of a little more than a century of effort, our understanding of the world of atomic and subatomic physics went from a vague understanding of atoms, to one that is much more detailed. Early in this hundred-year-long period, we learned about electrons (1897), then how they circle a dense nucleus (1911), followed by the discovery of the protons (1917) and neutrons (1932) that form the nucleus. From the 1930s onward, researchers used both cosmic rays and particle accelerators to discover antimatter (1932), and particles that don't exist in atoms (e.g., the muon [1936] and neutrino [1956], as well as a huge number of others[1]).

The year 1962 brought the discovery that there existed multiple neutrinos, and, a few years later, scientists realized that there were smaller particles called quarks inside protons and neutrons (1964). During the 1970s, the quark idea was validated, and it was discovered that there were ephemeral quarks that were not found in atomic nuclei but are impermanent and have an evanescent existence. These particles exist only inside collisions made by particle accelerators and earlier in the Big Bang. The year 1995 brought the discovery of the heaviest subatomic particle ever known, the top quark, with a mass 184 times heavier than a proton—approximately the same as a tungsten nucleus.

Rounding out our whirlwind history of particle physics, the year 2000 heralded the discovery of a third kind of neutrino, and 2012 was the year when scientists discovered the Higgs boson, the particle that provides strong evidence for the existence of the Higgs field, which gives mass to all structureless subatomic particles. For a reader who wants to delve more deeply into this fascinating history, Ref. 2 gives several books that are well worth your time.

The information discovered over the last century has led scientists to devise what is called the Standard Model of particle physics. A particle ensemble of six quarks, three charged leptons, and three neutral leptons can explain the makeup of all ordinary matter. These particles are all fermions. Researchers then add the four known forces (electromagnetism, the strong and weak nuclear forces, and gravity) to the mix to hold the particles together and to guide their motion as they move through space. Three of those forces are well understood in the quantum realm and each force is generated by one or more bosons that are exchanged between the fermion matter particles. For the known forces, we know of the following force-mediating bosons: electromagnetism (photon), the strong nuclear force (gluon), and the weak nuclear force (the W and Z bosons). A validated theory of quantum gravity does not exist, but a hypothetical particle called a graviton is postulated as mediating gravity. Finally, there is the Higgs boson, the most recently discovered subatomic particle, which is the particle manifestation of the Higgs field, and gives mass to the quarks, leptons, and force-carrying bosons. Figure 1 illustrates the known particles of the Standard Model.

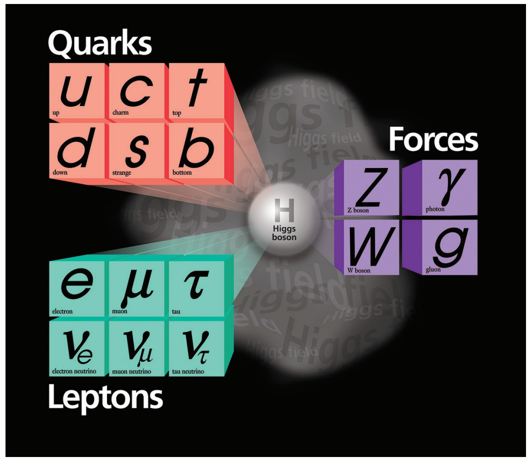

Fig. 1. The Standard Model consists of six quarks, six leptons, and four force-carrying particles. The Higgs field permeates space and gives mass to some subatomic particles.

Far more detail can be found in Refs. 2 and 3. Reference 4 gives a more academic level description.

Early particle accelerators

While some of the discoveries mentioned above (e.g., antimatter, the muon, and others not mentioned) were made using cosmic rays from space, the vast majority were found in particle accelerators. There are many types of accelerators, but roughly speaking, scientists use electric fields (sometimes static, but usually oscillating) to accelerate charged particles to very high speeds—often approaching the speed of light. The accelerators also use an array of dipole, quadrupole, and even higher n-pole magnets to guide and focus the beams of particles to a collision point. That collision point could be a stationary target, usually consisting of liquid hydrogen, but for some studies the target runs the entire gamut of elements. However, to reach the highest collision energies, two counterrotating beams are collided together head on. High-energy colliders have dominated our ability to study the highest energy interactions for half a century.

The beams of particles run the gamut of subatomic particles. Protons, electrons, and various atomic nuclei (bereft of their electron clouds) are the most common. However, antimatter electrons (also called positrons), antiprotons, and more unfamiliar particles like pions and muons are sometimes used. Pions are particles with a mass of about 15% that of the proton and are made of a mixture of up and down quarks and antimatter quarks. They exist for only 2.6×10^{-8} seconds. Muons are heavier cousins of the electron, with a mass similar to a pion, and they live for only 2.2×10^{-6} seconds. Relativistic effects induced by particle accelerators can extend their lifetime by large factors.

The history of particle accelerators begins in the late 1800s, with the invention of such things as Crookes tubes and similar devices.[5] The Crookes tube used a heated cathode and a

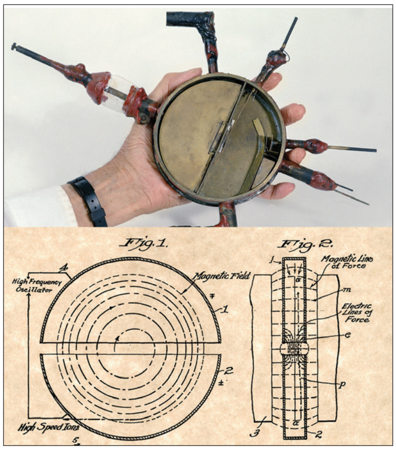

Fig. 2. Lawrence's original cyclotron (top) and an extract from his 1932 patent application, showing the basic geometry of the accelerator, plus the path of a charged particle inside it.

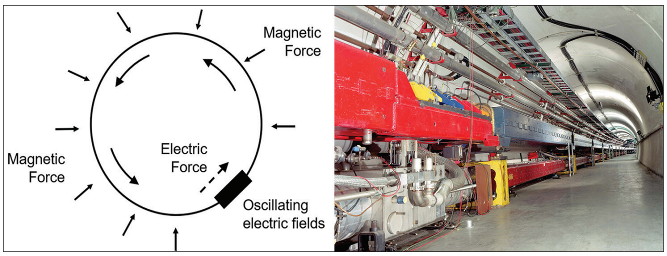

Fig. 3. Simplified description of a synchrotron (left). Two of Fermilab's synchrotrons (right). The top ring of magnets comprise the Main Ring and the bottom comprise the legendary Tevatron. Blue magnets are dipoles and red magnets are quadrupoles.

strong electric field. The heated cathode copiously emitted electrons, and the electric field accelerated them towards a waiting anode. A Crookes tube was instrumental in both the discovery of x-rays and electrons.[2]

Over the course of decades, particle accelerators using this simple technology were improved. The electric fields were raised until the beams were able to accelerate beams of particles to energies of about 1 MeV. At that energy, the breakdown voltage of accelerators of the time would cause sparks, and this required that a new technology be devised.

In 1930, Ernest Lawrence invented the first circular particle accelerator.[6,7] This particular design is ingenious, as it is able to reuse the same electric field over and over again, rather than making a single, very strong, electric field. For example, if a particle can be made to pass through a 100-kV electric field 10 times, that's equivalent to passing through a 1-MeV uniform electric field once. This reduces the voltages inside your accelerator.

Lawrence's design is called a cyclotron. Two D-shaped metal containers are oriented so the flat faces are parallel to one another, separated by a short distance. These D-shaped containers are hollow, with an open face along the flat side, but with a wall along the curved sides. The D's are then located in a uniform magnetic field, supplied by an external electromagnet (although sufficiently powerful permanent magnets also work). Between the flat faces of the D's, an oscillating electric field is set up with a frequency that is exactly half the time for a charged particle to travel in a circular-ish path inside the D's. In this way, as the particle transits one D, the electric field reverses itself so it is pointing in the correct direction to accelerate the particle again.

Because in each circuit the velocity of the particle increases, the radius of its orbit increases. The net outcome is a spiral path of the charged particle. As long as the velocity of the particle does not become relativistic, the frequency of the oscillating electric field is unchanged, making it an ideal problem for introductory physics students to solve. Lawrence's first cyclotron was five inches in diameter and could accelerate hydrogen ions to an energy of 80 keV. He later went on to make a series of ever more powerful cyclotrons, culminating in one with a 60-inch diameter device, which accelerated protons to an energy of 16 MeV. This was the accelerator with which both plutonium and neptunium were discovered by other researchers. His final foray into this technology was the 184-in synchrocyclotron (discussed below), with a whopping beam energy of 730 MeV.

When relativistic effects come into play (at about a few percent the speed of light), a standard cyclotron no longer works. The relativistic mass and momentum of the beam particle cause the beam orbits to be asynchronous with the oscillating electric field. Two designs overcame this limitation—the synchrocyclotron, which slowly changed the frequency of the oscillating electric field to compensate for relativistic effects, and the other is the isochronous cyclotron, which modified the magnetic field surrounding the accelerating cavity. Both techniques could squeeze out a little more performance, but a new technology was needed. Lest one think that cyclotron technology is no longer useful, approximately 1500 cyclotrons are currently in operation to provide radioactive nuclides for various medical applications.[8]

Synchrotrons

Synchrotrons are a huge improvement over the earlier cyclotron technology. Essentially, they are a ring of dipole electromagnets, with a short portion of the circle making up the accelerator geometry dedicated to an oscillating electric field. Figure 3 shows the basic idea of a synchrotron, as well as the Fermilab Tevatron, which was the highest energy particle accelerator in the world from 1986 to 2011.

The first synchrotron was built in 1946 by Frank Goward and D. E. Barnes.[9] This type of accelerator would raise the magnetic field of the magnets to take into account the increased energy. Using the familiar equations for orthogonal motion and magnetic fields, $F = qvB = \gamma mv^2/r$, one can easily derive a relationship between momentum and magnetic field; one gets $B = p/(qr)$. Thus, as the momentum of the beam increases as the particles circle the accelerator, the magnetic field must increase in a linear fashion.

In addition, the frequency of the electric field must be adjusted as the momentum of the particle transitions from non-relativistic to ultra-relativistic. At ultra-relativistic speeds, the velocity of the particle no longer increases, and changes in the frequency become less necessary.

Synchrotrons were the workhorses of the 1950s and 1960s and remain so today. It was in synchrotrons that hundreds of new particles were discovered and that this particle zoo,[1] as it is often called, provided the data necessary to formulate the Standard Model of particle physics. Synchrotrons have been constructed to accelerate electrons, protons, and heavy ions. Over the decades, a series of accelerators were built, each with an increase in collision energy compared to their predecessor. Figure 4 illustrates the trends from the 1960s through the present day.

Large Hadron Collider

The current queen of synchrotrons is the Large Hadron Collider, or LHC.[10] It is located just west of Geneva, Switzerland, and it is the highest energy particle accelerator in the world. It accelerates two beams of protons in counterrotating directions and collides them together. Each beam has a momentum of 6.5 TeV/c, resulting in a collision energy of a staggering 13 TeV. It began operations in 2008, but shortly after accelerating particles, a devastating electrical short caused serious damage, requiring over two years to repair. Once the repairs were completed, some initial beam tests began in 2010, with real operations beginning in 2011 at half the design energy, resulting in collisions with a center of mass energy of 7 TeV. In 2012, the LHC raised its collision energy to 8 TeV.

Using the data recorded in 2011 and 2012, scientists at the LHC were able to discover the Higgs boson, the last missing piece of the Standard Model. It was a triumph of modern physics and resulted in the 2013 Nobel Prize in Physics being awarded to Peter Higgs and Francois Englert, two of the theoretical physicists who proposed the Higgs field back in 1964.[2] Englert's collaborator, Robert Brout, died in 2011 and was unable to see the validation of his work, and was also unable to share the Nobel Prize, as the prize is never awarded posthumously.

It has been nearly a decade since the Higgs boson was discovered and the LHC has operated superbly. Four experiments (ALICE, ATLAS, CMS, and LHCb) arrayed around the accelerator have published over 2000 refereed papers. Many of the papers have validated the Standard Model, but the vast majority of papers have been searches for physics beyond the Standard Model. Aside from a few tantalizing hints that have faded away as the experiments gathered more statistics, there has been little to celebrate. As of this writing, the LHCb has collected evidence that matter and antimatter are not treated on equal footing in the Standard Model.[11] Given that this prediction runs counter to currently accepted theory, these data are of interest to many theorists. However, the deviations from the Standard Model are modest, and the community is not ready to claim that the Standard Model is broken.

The future

Many researchers expected that the LHC would be an accelerator that discovered phenomena outside known physics. Supersymmetry[12] and large extra dimensions[13] were two popular theories. However, neither of these have been validated. Indeed, the data have ruled out many models based on these ideas.

So, the question becomes, "Now what?" If the LHC is not the discovery machine that scientists had hoped, what sort of accelerator should researchers build? Indeed, it is reasonable to ask if any future accelerator should be built. The price tag for the LHC was about $10 billion. A future accelerator will likely cost that or even more.

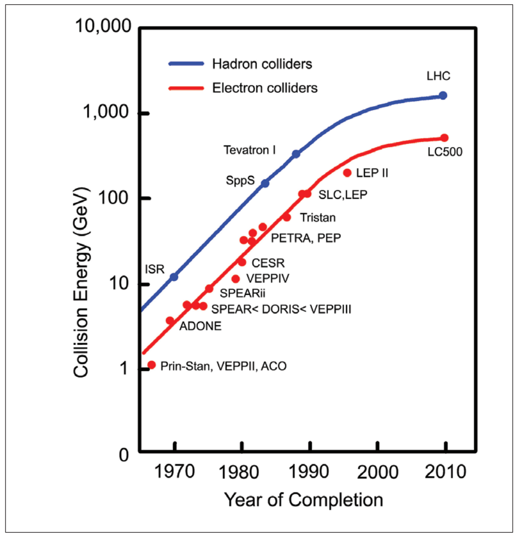

Fig. 4. The collision energy of a gamut of electron and hadron colliders on the date where they began operation. Difficulties in technology are responsible for the deviation from the semi-log behavior that persisted for decades. LC500 is a proposed accelerator that has not yet been built. (Original image inspired by M. Tigner.)

There have been many possible future plans for accelerators to be built to replace the LHC. The simplest to describe is called the High Luminosity LHC, or HL-LHC.[14] This simply requires upgrades of some of the LHC components, and it is currently under way. It will begin operations in a few years, perhaps in 2027, although Covid considerations have caused inevitable delays. It is expected that this machine will run through 2040. But the HL-LHC will only increase the collision rate. It will not significantly increase the collision energy.

There is another proposed accelerator that could take over for the LHC. It is the International Linear Collider, or ILC.[15] The ILC will collide electrons and antimatter electrons at the much lower energy of 250 GeV. The beams and collision energy were chosen to make the ILC a Higgs factory, exploring the properties of the Higgs boson in detail. The accelerator is envisioned to be located in Japan; however, the Japanese government has not committed to funding it.

Perhaps the most ambitious of the future prospects in accelerator technology is the Future Circular Collider, or FCC.[16] There are competitor projects, but they have many commonalities. The FCC is envisioned to be located at CERN, with the existing LHC as part of the accelerator chain that supplies beam to the FCC. It is expected to have a circumference of 100 km and a collision energy of 100 TeV. This accelerator will provide a collision energy of approximately seven times the LHC. This project has not been approved. It will not begin construction for over a decade and its price tag runs in the area of $20 billion, most of it coming from Europe, but with international funding. If built, it is expected to run until 2070.

This price tag has raised eyebrows and some skepticism from even the particle physics community. Perhaps the most vocal critic is Sabine Hossenfelder, a theorist with particle physics training, but who has moved on to other interests.[17] She criticizes the cost of the FCC, suggesting that the money could be better spent on smaller projects, each focused on a small number of (or a single) outstanding mysteries of particle physics. She also, quite correctly, points out the fact that there is no theoretical reason to expect that new physics will manifest itself with a factor of seven in collision energy. At least with the LHC, we had ample reason to expect that scientists using the accelerator would discover, or falsify, the Higgs boson. But for the FCC, there is no corresponding and universally accepted theoretical goal.

On the opposing side, there are many who note that particle physics is an experimental science and we should not make decisions simply because theoretical scientists have not worked out a well-regarded theory. It is certainly possible that a factor of seven in increased collision energy could make discoveries that will revolutionize science. One such possibility would be the creation and discovery of dark matter in the laboratory (if indeed dark matter exists). Another strong counterargument for building a future machine is to maintain the infrastructure and knowledge required to build large particle accelerators. If, after the LHC completes its run in 2020, there are no future accelerators in the future, the collider community will disperse and it will take a generation to recover that capability.

The decision is a difficult one and the European and American particle physics communities are grappling with it, weighing the options, and making funding recommendations to the respective governmental agencies that support high-energy physics. The European process completed in 2020,[18] and the American process is ongoing.[19] Active discussion among opposing points of view will hopefully lend clarity to the proper decision.

Either way, outstanding questions of particle physics, like the nature—indeed the existence—of dark matter, the origins of the matter/antimatter asymmetry in the universe, the question of whether the known forces unify, and if the known quarks and leptons are themselves made of smaller particles, all beg for answers. Then there is the question of why the Higgs field exists and the huge discrepancy in energy we see between the Higgs field and dark energy. This is actually an enormous problem with dark energy and quantum field theory. Both of these theories predict an energy density in space. The energy densities predicted by standard quantum field theory and dark energy differ by the staggering factor of 10^{120}, perhaps the largest disagreement in physics of all time. Such a discrepancy is clear evidence that we don't understand dark energy or quantum field theory (or both!). Progress in all of these is necessary to advance towards a thorough understanding of the universe. The path forward is not clear, but this is often true in frontier science. And hopefully discussions currently being held across the globe will help us decide the best way to go.

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