Volker Ziemann

Beams

The Story of Particle Accelerators and the Science They Discover

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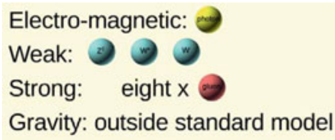
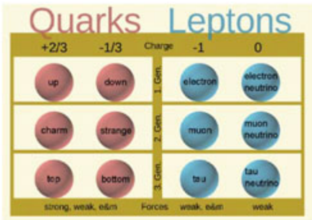
Forces (all of them Bosons)



Particles (all of them Fermions)



Quark composites

Higgs Boson 

Preface

Several years ago, when tying my shoelaces after a visit to our local swimming pool, I overheard two teenagers excitedly discussing the Omega-minus particle. Not believing what I heard, I started talking to them and they confirmed that it was all about particle physics and their enthusiasm about the subject was contagious. Ever since, thinking about this encounter has put a smile on my face and made me optimistic about the future of my field, which is physics, accelerator physics to be more specific. As a day's job I work with particle accelerators, among them were synchrotron radiation sources, a linear collider, the large hadron collider, a free-electron laser, and a small storage ring used for nuclear physics experiments.

Coming from the accelerators I thought it is prudent to complement the many great nonfiction books about particle physics[1] with one covering the role that accelerators played in the game. After all, progress in both fields, particle physics and accelerators, is mutually contingent. New accelerators enable discoveries of new particles and new theories make predictions that motivate building new accelerators to validate them. This give-and-take forms one thread that runs through this book.

And progress is rarely smooth. More often, long tranquil periods of gradual improvements are punctuated by great ideas or great inventions that, all of a sudden, open radically new possibilities. The Internet and the world-wide web are examples from everyday life; they fundamentally changed the way we interact with each other and how we do business. In a similar vein, other great ideas boosted the performance of particle accelerators and others yet, our understanding of the subatomic world. These great ideas form the second thread that runs through this book.

While fleshing out the threads I had my two teenagers in mind as prototypical readers, or anyone else who might read *New Scientists* or *Scientific American*. The latter was my favorite magazine when I was a (late) teenager with similar interests—yes, I was probably a nerd before the word entered popular culture. At the time, I ordered many reprints of older articles that I recently unearthed in my basement. Among them were gems like Erwin Schrödinger's article *What is Matter?* explaining that sometimes particles behave like, well, particles and sometimes like waves. Rereading many of these old articles I decided to settle for a similar style: no formulas (except $E = mc^2$) and many illustrations to convey ideas and to describe technologies. Basically, I wrote this book for myself as a teenager. You'll be the judge whether that works for you as well, dear reader.

Throughout this book, you'll find references to these reprints, both from Scientific American and from other sources. They provide extra background to selected topics that should be relatively easy to access via public libraries. I collected direct links to most of the articles on https://github.com/volkziem/Beams. Again, often libraries can help to access material behind paywalls. In case you wonder, the Omega-minus and the corresponding magazine article are featured in Chap. 6.

I am grateful to my colleagues and my diligent proof-readers, in particular Stefan Leupold, Roger Ruber, Björn Persson, Ingvar Ziemann, Ellen Matlok-Ziemann, and Elin Bergeås-Kuutmann. All remaining blunders are, of course, mine. If you spot one, don't keep it but rather tell me about it.

Uppsala, Sweden Volker Ziemann

Note

1. Leon Lederman, *The god particle*, Dell publishing, New York, 1993; Frank Close, *Particle Physics, a very short introduction*, Oxford University Press, Oxford, 2004; Lisa Randall, *Higgs discovery, the power of empty space*, Ecco press, New York, 2013; Harald Fritzsch, *Quarks, the stuff of matter*, Basic books, New York, 1983.

Contents

1

Introduction

A few years ago my publisher set up a web page entitled "What is Physics?" and asked me to contribute an answer. I came up with:

> It's figuring out the world we live in and building the instruments to help with the figuring![1]

One key moment of this figuring process was the press conference at the European Laboratory for Particle Physics (CERN)[2] in the summer of 2012 where the discovery of a new particle was announced.[3] This new particle, known as the *Higgs boson*, was the last missing part of, arguably, the greatest conceptual framework ever conceived by the human mind, the *standard model of elementary particles*.[4] It describes no less than all fundamental interactions and all elementary particles that make up our world.

That this press conference was held at CERN was no coincidence; CERN is the home of one of the largest instruments on earth, the *Large Hadron Collider* (LHC), a 27 km long string of magnets in an underground tunnel close to the city of Geneva in Switzerland. Inside this tunnel, two counter-propagating beams of protons—nuclei of hydrogen atoms—are accelerated very, very close to the speed of light, before they are smashed head-on into each other, creating conditions very similar to those just after the birth of our universe—the Big Bang. Only in these extreme conditions certain elementary particles, among them the Higgs boson, reveal their existence to the large particle-physics detectors ATLAS and CMS.[5]

Getting to the point of observing the Higgs boson required loads of ingenuity, both in "figuring" and in building the instruments. In this book we'll follow the co-evolution of particle physics and of accelerators for the past 150 years.

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Along the way we'll highlight transformative technologies—superconductivity is one example—and "great ideas"—using radio-frequency waves to accelerate particles is another—that made new generations of accelerators possible. Subsequently these new machines satisfied the theoreticians' need for experimental evidence to prove or disprove their wildest ideas. Occasionally their predictions of new particles stimulated building new accelerators; LHC is an example. At other times, experiments at accelerators revealed new particles whose existence flabbergasted the theoreticians and stimulated new theories. An example is the "particle zoo" that grew at an alarming rate in the early 1960s. The dialectic relationship between theories and accelerators will be our guide throughout the book.

Another thread running through this book is the concept of a *scattering experiment*. It is based on smashing things into each other and observing what comes out. This idea extends from Rutherford's experiments a century ago until today's experiments in the LHC. Rutherford and his collaborators directed particles, emitted from the recently discovered radioactive material radium, onto a thin foil of gold (Chap. 3) and observed recoiling particles with a fluorescent screen. In much the same way (Chap. 11) ATLAS and CMS observe whatever comes out after smashing the LHC beams into each other.

Whereas the energy of the radium emissions allowed Rutherford to probe the structure of atoms, much higher-energy probes are needed to explore the inside of atomic nuclei. This is a consequence of the quantum mechanical nature of matter that becomes important in the microscopic world. Matter sometimes behaves as a particle and sometimes as a wave,[6] whose wavelength depends on its mass and the speed. The larger their product (mass times speed) is, also referred to as the particles' momentum, the shorter the wavelength is.[7] And a large momentum also means that a particle has a large energy. The trick is thus to accelerate particles to very high energies to make them behave as short-wavelength probes that can "see" structures having sizes comparable to their wavelength (Fig. 1.1). All electron microscopes[8] rely on this quirky feature of the quantum world and so does LHC, albeit with protons.

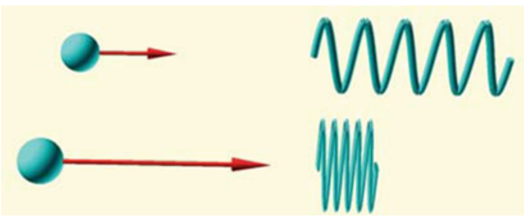

Fig. 1.1 The corresponding wavelength of a faster particle (front) is shorter

As particles reach higher and higher speeds and energies they enter the realm of Einstein's[9] theory of relativity. It predicts that the speed of particles can only increase up to the speed of light as the ultimate speed limit. But where does the energy go when it cannot increase the speed of particles? Einstein found that instead their mass m increases; so energy is going into the mass. As a consequence, even at rest, mass represents some amount of energy E, given by Einstein's famous equation $E = mc^2$ where c denotes the speed of light. Throughout, we will use this equivalency between mass and energy to specify the mass of particles. Writing numerical values for specific particles, however, quickly becomes tedious, because the mass of particles is very small and the speed of light is very large. The large number of zeros that need to be written becomes rather cumbersome. This calls for a more efficient notation.

Scientific and Prefix Notation

Light reaches the moon in a little over a second because it travels at the incredibly high speed of close to 300 000 000 meters per second. Finding the equivalent energy of some mass with $E = mc^2$ even requires squaring this large number, which results in a number with sixteen zeros. Since handling these large numbers becomes rather tedious, a shorthand notation was invented. Noting that the initial "3" is followed by eight zeros, we write this number as 3.0×10^8. Converting between these two notation is easy; 10^8 just instructs us to move the decimal point in 3.0 eight places to the right. This simple rule also works for negative numbers in the exponent. We only have to move the decimal point to the left; 2.0×10^{-3} thus becomes 0.002. Using this "move decimal point" rule makes it obvious that we can add the exponents of numbers; $3 \times 10^8 \times 3 \times 10^8$ thus simplifies to 9×10^{16}. This scientific notation will save me from writing and you from reading a lot of zeros.

And there is another space saver in store. We all know that the prefix "k" for *kilo* translates into "one thousand" or 10^3; a kilometer is one thousand meters. Instead of writing "kk", the prefix "M" for *mega* translates to one million or 10^6. By convention, for every factor of 1000 a new prefix is introduced: "G" for *giga* or 10^9, "T" for *tera* or 10^{12}, and "P" for *peta* or 10^{15}.

In much the same way small numbers are described by prefixes. The letter "m" for *milli* denotes "one thousandth" or 10^{-3}; there are one thousand millimeters in a meter. Again, every factor of 1000 smaller numbers are described by a new prefix: "μ" for *micro* or 10^{-6}, "n" for *nano* or 10^{-9}, "p" for *pico* or 10^{-12}, and "f" for *femto* or 10^{-15}. There are additional prefixes beyond those introduced here, but we will not need them. We will, however, liberally use both the prefix and scientific notation throughout.

Unification

But let us get back to physics and the people that work in the field. One principle that guides the thinking of many physicists is a desire to *explain as many phenomena as possible based on as few assumptions as possible.* This is what physicists call *unification.* The "many phenomena" come of course from experiments, often done with accelerators, whose results are distilled into an underlying framework that we then call a "theory." Much of the theory-building process involves the *classification* of observations in order to identify systematic traits. In high-energy physics that will concern us throughout this book these traits are common features of groups of elementary particles. Once such a feature is found, we give it a name such as "strangeness" (Chap. 5) or "charm" (Chap. 8). In other words, we invent a classification scheme. Only later, a mathematical framework emerges to explain this classification and to predict new features that are hopefully verified in new experiments. In the physics of the subatomic world this cycle of experiments, classification, and theoretical unification repeats itself over and over again leading to the current state of the art. This is the standard model of elementary particles with the Higgs boson announced at the press conference at CERN.

This desire to explain the world, however, started much earlier. Already in the seventeenth century, based on Tycho Brahe's celestial observations, Johannes Kepler[10] deduced laws, today called "Kepler's laws," for the motion of planets around the sun. At about the same time Galileo Galilei[11] found laws that govern falling bodies on earth. About a century later, Isaac Newton[12] "unified heaven and earth" by formulating a theory that encompasses things happening on earth and in the sky. He even derived Kepler's laws from his "unified theory of gravity." In the beginning 20th century Einstein went one step further and, in his general theory of relativity, extended the scope to even describe different universes. That's some unification!

In much the same way electricity, first explored by Benjamin Franklin and Alessandro Volta,[13] and magnets, explored by Ampere, Oersted, and Faraday,[14] were unified by James-Clerk Maxwell.[15] He found equations, today bearing his name, that placed electricity and magnetic phenomena in a common framework. He encapsulated all observations and empirical laws found by his predecessors into just four equations—as we write them today. They describe how the central quantities of his theory, the electric and magnetic fields, behave. And these equations could do so much more than just explain previous observations. They predicted new phenomena that were soon experimentally found: electro-magnetic waves are an example. Today we use them to communicate via smartphones and to accelerate particles in accelerators. Even the design of magnets that guide particles in accelerators is based on Maxwell's equations.

Gravity and electromagnetism are two of the four fundamental forces found in nature. The inside of this book's front cover shows a brief summary of our current understanding of the four natural forces and particles that may serve as a reminder and a road-map on our journey through history. The two other forces are known as the "weak" force (or weak interaction) and the "strong" nuclear force (or strong interaction). They only make themselves known in the subatomic or nuclear realm. The former plays a central role in the spontaneous decay of particles that characterizes *radioactivity*. The strong nuclear force, on the other hand, is responsible for the stability of atomic nuclei. The existence of both interactions was only realized in the 1930s. But from then on they play a key role in the development of the standard model of particle physics. Check out the time line of the co-evolving history of accelerators and the physics of elementary particles in the back of the book. You'll see that this time line started a bit earlier. As a matter of fact, accelerator prehistory started only a few years after Maxwell had published his theory.

Notes

1. The complete answer is actually a bit longer. Here it is: "Physics? It's figuring out the world we live in and building the instruments to help with the figuring! Let me elaborate: physics strives to understand the inner workings of natural and technical phenomena and explains complex processes through a few basic assumptions. But validating this reasoning involves experiments that often require instruments beyond the state of the art: for example, telescopes that scan the universe to detect radio and gravitational waves, and cutting-edge experiments at particle accelerators, which are used to examine the microscopic world."
2. CERN is the acronym for *Conseil Européen pour la Recherche Nucléaire*, the original French name for the lab.
3. You can watch the press conference on https://www.youtube.com/watch?v=AzX0dwbY4Yk and the press release is available from https://home.cern/news/press-release/cern/cern-experiments-observe-particle-consistent-long-sought-higgs-boson.
4. There are strong indications that there is much more, but we postpone that discussion to the epilogue.
5. Peter Higgs (b. 1929) and Francois Englert (b. 1932) received the Nobel Prize in Physics in 2013 "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently

was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider."

6. Erwin Schrödinger, *What is Matter?* Scientific American, September 1953, page 52. George Gamow, *The Principle of Uncertainty,* Scientific American, January 1958, page 51.
7. The relationship between the wavelength and the momentum of a particle was first proposed by Louis de Broglie (1892–1987) who received the Nobel Prize in Physics in 1929 "for his discovery of the wave nature of electrons." Importantly, it stimulated Schrödinger to formulate the wave equation that bears Schrödinger's name to describe the motion of electrons in atoms.
8. Electron microscopes focus accelerated electrons to tiny spot sizes (nanometer and even below) and observe electrons or X-rays that are knocked out from the surface. For an overview, see: Thomas Everhart and Thomas Hayes, *The scanning electron microscope,* Scientific American, January 1972, page 54.
9. Albert Einstein (1879–1955) was born in Germany, but emigrated to the US in 1933 after the Nazis came to power in Germany. He fundamentally changed our conception of space and time with his special theory of relativity that he published in 1905, the same year he published an explanation of the photo-electric effect (Chap. 3) in terms of photons. He was awarded the Nobel prize in Physics in 1921 "for his services to theoretical physics, and especially for his discovery of the law of the photoelectric effect." Introducing photons—quanta of light—also made him one of the founding fathers of quantum theory. His life's story is told by many biographers, among them his associate and his secretary: Banesh Hoffmann and Helen Dukas, *Einstein, the Human Side,* Princeton University Press, Princeton, 1972 and Ronald Clark, *Einstein, Life and Times,* Avon books, New York, 1971.
10. Already before the advent of optical telescopes, the Danish astronomer Tycho Brahe (1546–1601) recorded tables with the positions of many celestial objects using a so-called *astrolabe,* a device to accurately determine the positions of stars or planets above the horizon. Based on Brahe's tables, Johannes Kepler (1571–1630) discovered that planets follow elliptical orbits and that the size of the ellipse is related to time a planet needs to complete one revolution. At the same time of taking a large step towards our modern attitude toward sciences Kepler had one foot in the medieval traditions of his day. He prepared horoscopes for dignitaries and had to see his aunt burning at the stake and protect his mother from the same fate. For a short account of his life's story, see: Florin Cajori, *Johannes Kepler,* The Scientific Monthly, May 1930, page 385.
11. Transcending the scholastic, scripture-based science of his day with practical experiments, Galileo Galilei (1564–1642) found that heavier objects fall down as fast as lighter objects and that the periodicity of a pendulum only depends on its length, but not on its weight. This makes him the father of modern scientific methodology. He even applied it to the heavens, by using optical telescopes to observe the moons of Jupiter.
12. Isaac Newton (1642–1727) formulated basic laws that govern the motion under the influence of forces. Moreover, he developed a new field of mathematics, dif-

ferential calculus, that, together with his laws, made it possible to describe not only Galileo's, but also Kepler's observations. The publication of his "Principia Mathematica" sets the starting point of what today is known as the field of "classical mechanics". His life's story is told in: Bernard Cohen, *Isaac Newton,* Scientific American, December 1955, page 73.

13. Benjamin Franklin (1706–1790) invented the lightning rod to give lightnings a safe route to ground without igniting a building on the way. He thus identified electricity as a flowing entity that occurs in two polarities. Alessandro Volta (1745–1827) constructed the first batteries and gave all scientists since a controlled source of electricity for experiments. Read about his life and discoveries in: Giorgio de Santillana, *Alessandro Volta,* Scientific American, January 1965, page 82.
14. Hans-Christian Oersted (1777–1851) discovered that electric currents create magnetic fields that turn the needle of a compass, an observation that incited Andre-Marie Ampere (1775–1836) to study the relationship of electric and magnetic phenomena further. In particular, he noted that two current-carrying wires attract each other and that coiled-up wires, he called such devices *solenoids*, generate much higher magnetic fields than individual wires. Michael Faraday (1791–1867) discovered that time-varying magnetic fields produce electric currents, a process he named *induction*, and used it to construct electric motors and generators. Importantly, Faraday introduced the concept of electric and magnetic *field lines.* Being asked by a politician about the usefulness of electricity, he purportedly answered "One day, sir, you will tax it." How true! Faraday's remarkable development from bookbinder apprentice to Fellow of the Royal Society is described in: Herbert Kondo, *Michael Faraday,* Scientific American, October 1953, page 90.
15. James-Clerk Maxwell (1831–1879) condensed all experimental evidence regarding electric and magnetic phenomena into a concise set of four equations (based on Newton's differential calculus). Apart from predicting the existence of radio waves, he was able to derive their speed of propagation from a few fundamental constants. Remarkably, his equations already incorporate concepts from Einstein's relativity. As a matter of fact, Einstein's first paper on relativity actually deals with this aspect. Maxwell's life and work are told in: James Newman, *James Clerk Maxwell,* Scientific American, June 1955, page 58.

2

Accelerator Prehistory

Around 1875, only a few years after Maxwell had published his theory, William Crookes[1] decided to figure out what electricity really is and built the apparatus, today named *Crookes tube* and shown in Fig. 2.1, to help him with figuring. It is probably the first device that can be called particle accelerator.

In order to be able to observe some electricity-related signal, he covered one end of an evacuated glass tube with luminescent paint that lights up when it is hit by radiation. Moreover, he placed two electrodes inside the tube; one of them formed like a Maltese cross. He then connected these electrodes with cables to the poles of a high-voltage power supply. Nothing showed up on the screen when he connected the positive pole of the power supply to the electrode furthest away from the screen. Reversing the polarity and connecting the negative pole to the distant electrode, the screen lit up with a shadow of the Maltese cross clearly visible. Apparently, "something" came from the distant electrode and traveled towards screen, but was intercepted by the Maltese cross, thus casting its shadow. Since the electrode connected to the negative pole of a power supply was historically called *cathode,* the "something" was called *cathode rays*. The electrode, connected to the positive pole—the Maltese cross—was called *anode*; it seemed to attract these rays.

The high voltage was created by an early relative of the ignition system used in older cars with ignition coil and spark plug. Here a battery powers a coil, called *induction coil*, to generate a magnetic field inside. Rapidly interrupting the current flowing through the coil creates a large surge of voltage, a phenomenon called *induction* that was already described by Maxwell's theory. At the time, like today, creating the high voltages needed to accelerate particles was a formidable challenge and required quite a bit of ingenuity.

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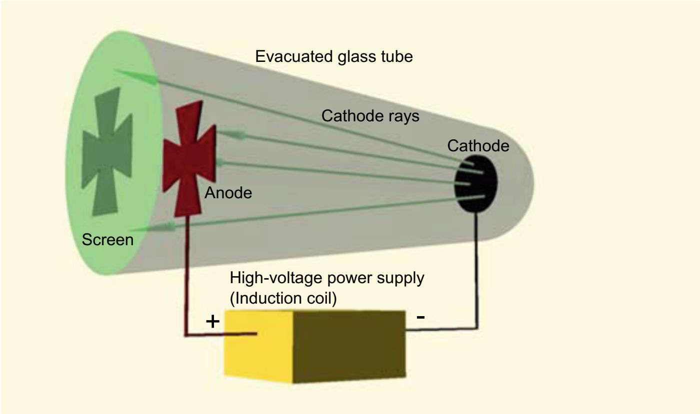

Fig. 2.1 Crookes tube and induction coil based high-voltage source

But let's get back to the rays. Since they move from the negative pole of the high voltage generator to the positive pole, Crookes deduced that these rays are negatively charged. Moreover, he found that they move *parallel* to the electric field between the electrodes. The rays appeared to experience a force that pulls and accelerates them towards the positive pole. Later, Crookes investigated the effect of magnetic fields on the rays and found that they deflect these rays in a direction *perpendicular* to the magnetic field. These two fundamental observations

- electric fields increase energy of charged particles;
- magnetic fields deflect charged particles;

are the basis for practically all accelerators built ever since.

A little over 20 years later in 1897, J. J. Thomson[2] used an apparatus very similar to the Crookes tube. But he added a well-calibrated magnetic field perpendicular to the motion of the cathode rays, which are consequently deflected. For a particular type of particle the deflection angle provides a specific "fingerprint." Heavier particles are deflected less with the same magnetic field and lighter particles are deflected more. Moreover, from the direction of the deflection, either left or right, he deduced that the polarity of the particle is negative. Today, Thomson's measurement device with deflecting magnet is called a *spectrometer* (Fig. 2.2). It is used in practically all particle detectors to identify the type of particles. Henceforth, J. J. Thomson's particle was called *electron*, the first fundamental particle.