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Particle Physics

Quarks, Leptons, and the Standard Model

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Chapter 1: The Discovery of Particle Physics

The recent weighing of the neutrinos dealt the bookkeeping its first measured crack: the theory's original text assigned those ghostly particles no mass whatsoever, and the experiments proved them weighty, the crack that opened the current renovation of the whole account.

Modern particle physics research is focused on subatomic particles, including atomic constituents, such as electrons, protons, and neutrons (protons and neutrons are composite particles called baryons, made of quarks), that are produced by radioactive and scattering processes; such particles are photons, neutrinos, and muons, as well as a wide range of exotic particles.

All particles and their interactions observed to date can be described almost entirely by the Standard Model. Dynamics of particles are also governed by quantum mechanics; they exhibit wave–particle duality, displaying particle-like behaviour under certain experimental conditions and wave-like behaviour in others. In more technical terms, they are described by quantum state vectors in a Hilbert space, which is also treated in quantum field theory.

Following the convention of particle physicists, the term elementary particles is applied to those particles that are, according to current understanding, presumed to be indivisible and not composed of other particles. Ordinary matter is made from first-generation quarks (up, down) and leptons (electron, electron neutrino). Collectively, quarks and leptons are called fermions.

They have a quantum spin of half-integers (−1/2, 1/2, 3/2, etc.) and obey the Pauli exclusion principle, where no two particles may occupy the same quantum state.

Quarks have fractional elementary electric charge (−1/3 or 2/3) and leptons have whole-numbered electric charge (0 or -1). Quarks also have color charge, which is labeled arbitrarily with no correlation to actual light color as red, green and blue. Because the interactions between the quarks store energy which can convert to other particles when the quarks are far apart enough, quarks cannot be observed independently. This is called color confinement.

There are three known generations of quarks (up and down, strange and charm, top and bottom) and leptons (electron and its neutrino, muon and its neutrino, tau and its neutrino), with strong indirect evidence that a fourth generation of fermions does not exist. Bosons are the carriers of the fundamental interactions: light's own force, the weak force that works decay, and the strong force that binds the nucleus. Light's own force rides on the photon, the smallest packet of light there is.

The strong interaction is mediated by the gluon, which can link quarks together to form composite particles. Due to the aforementioned color confinement, gluons are never observed independently. The Higgs boson gives mass to the W and Z bosons via the Higgs mechanism – the gluon and photon are expected to be massless. All bosons

have an integer quantum spin (0 and 1) and can have the same quantum state.

Since then the linear accelerator is being used for the Linac Coherent Light Source X-ray laser as well as advanced accelerator design research.

The theory that carries the field's whole account is the Standard Model: a framework of quantum fields, assembled across the century's middle decades, that describes every particle and force so far observed, with gravity alone standing outside its writ, and describes them to a precision no theory of anything has ever matched.

A key feature of the necessary field is that the field would have less energy when it had a non-zero value than when it was zero, unlike every other known field; therefore, the Higgs field has a non-zero value (or vacuum expectation) everywhere.

Various analogies have been used to describe the Higgs field and boson, including analogies with well-known symmetry-breaking effects such as the rainbow and prism, electric fields, and ripples on the surface of water.

For example, approximately 99% of the mass of baryons (composite particles such as the proton and neutron) is due instead to quantum chromodynamic binding energy, which is the sum of the kinetic energies of quarks and the energies of the massless gluons mediating the strong interaction inside the baryons.

Chapter 2: Understanding Particle Physics

Normal particles have positive lepton or baryon number, and antiparticles have these numbers negative. Most properties of corresponding antiparticles and particles are the same, with a few gets reversed; the electron's antiparticle, positron, has an opposite charge. To differentiate between antiparticles and particles, a plus or negative sign is added in superscript. For example, the electron and the positron are denoted e− and e+, respectively.

However, in the case that the particle has a charge of 0 (equal to that of the antiparticle), the antiparticle is denoted with a line above the symbol. As such, an electron neutrino is νe, whereas its antineutrino is νe. When a particle and an antiparticle interact with each other, they are annihilated and convert to other particles. Some particles, such as the photon or gluon, have no antiparticles.

A quark's color charges are called red, green and blue (though the particle itself has no physical color), and in antiquarks are called antired, antigreen and antiblue. The gluon can have eight color charges, which are the result of quarks' interactions to form composite particles (gauge symmetry SU(3)).

The neutrons and protons in the atomic nuclei are baryons – the neutron is composed of two down quarks and one up quark, and the proton is composed of two up quarks and one down quark.

A baryon is composed of three quarks, and a meson is composed of two quarks (one normal, one anti). Baryons and mesons are collectively called hadrons. Quarks inside hadrons are governed by the strong interaction, thus are subjected to quantum

chromodynamics (color charges). The bounded quarks must have their color charge to be neutral, or "white" for analogy with mixing the primary colors.

An atom is made from protons, neutrons and electrons. By modifying the particles inside a normal atom, exotic atoms can be formed. A simple example would be the hydrogen-4.1, which has one of its electrons replaced with a muon. The graviton is a hypothetical particle that can mediate the gravitational interaction, but it has not been detected or completely reconciled with current theories.

Many other hypothetical particles have been proposed to address the limitations of the Standard Model.

Notably, supersymmetric particles aim to solve the hierarchy problem, axions address the strong CP problem, and various other particles are proposed to explain the origins of dark matter and dark energy. The world's major particle physics laboratories are: Brookhaven National Laboratory (Long Island, New York, United States). Its main facility is the Relativistic Heavy Ion Collider (RHIC), which collides heavy ions such as gold ions and polarized protons.

It is the world's first heavy ion collider, and the world's only polarized proton collider.

Budker Institute of Nuclear Physics (Novosibirsk, Russia). Its main projects are now the electron-positron colliders VEPP-2000, operated since 2006, and VEPP-4, started experiments in 1994. Earlier facilities include the first electron–electron beam–beam collider VEP-1, which conducted experiments from 1964 to 1968; the electron-positron colliders VEPP-2, operated from 1965 to 1974; and, its successor VEPP-2M, performed experiments from 1974 to 2000. CERN (European Organization for Nuclear Research) (Franco-Swiss border, near Geneva, Switzerland).

Its main project is now the Large Hadron Collider (LHC), which had its first beam circulation on 10 September 2008, and is now the world's most energetic collider of protons. It also became the most energetic collider of heavy ions after it began colliding lead ions.

Earlier facilities include the Large Electron–Positron Collider (LEP), which was stopped on 2 November 2000 and then dismantled to give way for LHC; and the Super Proton Synchrotron, which is being reused as a pre-accelerator for the LHC and for fixed-target experiments. DESY (Deutsches Elektronen-Synchrotron) (Hamburg, Germany). Its main facility was the Hadron Elektron Ring Anlage (HERA), which collided electrons and positrons with protons.

The accelerator complex is now focused on the production of synchrotron radiation with PETRA III, FLASH and the European XFEL.

Fermi National Accelerator Laboratory (Fermilab) (Batavia, Illinois, United States). Its main facility until 2011 was the Tevatron, which collided protons and antiprotons and was the highest-energy particle collider on earth until the Large Hadron Collider surpassed it on 29 November 2009. Institute of High Energy Physics (IHEP) (Beijing, China).

IHEP manages a number of China's major particle physics facilities, including the Beijing Electron–Positron Collider II(BEPC II), the Beijing Spectrometer (BES), the Beijing Synchrotron Radiation Facility (BSRF), the International Cosmic-Ray Observatory at Yangbajing in Tibet, the Daya Bay Reactor Neutrino Experiment, the China Spallation Neutron Source, the Hard X-ray Modulation Telescope (HXMT), and the Accelerator-driven Sub-critical System (ADS) as well as the Jiangmen Underground Neutrino Observatory (JUNO). KEK (Tsukuba, Japan).

It is the home of a number of experiments such as the K2K experiment and its successor T2K experiment, a neutrino oscillation experiment and Belle II, an experiment measuring the CP violation of B mesons. SLAC National Accelerator Laboratory (Menlo Park, California, United States). Its 2-mile-long linear particle accelerator began operating in 1962 and was the basis for numerous electron and positron collision experiments until 2008.

As with theoretical physics, theoretical particle physics attempts to develop the models, theoretical framework, and mathematical tools to understand current experiments and make predictions for future experiments.

There are several major interrelated efforts being made in theoretical particle physics today. One important branch attempts to better understand the Standard Model and its tests. Theorists make quantitative predictions of observables at collider and astronomical experiments, which along with experimental measurements is used to extract the parameters of the Standard Model with less uncertainty. This work probes the limits of the Standard Model and therefore expands scientific understanding of nature's building blocks.

Those efforts are made challenging by the difficulty of calculating high precision quantities in quantum chromodynamics. Some theorists working in this area use the tools of perturbative quantum field theory and effective field theory, referring to themselves as phenomenologists. Others make use of lattice field theory and call themselves lattice theorists.

Another major effort is in model building where model builders develop ideas for what physics may lie beyond the Standard Model (at higher energies or smaller distances).

This work is often motivated by the hierarchy problem and is constrained by existing experimental data. It may involve work on supersymmetry, alternatives to the Higgs mechanism, extra spatial dimensions (such as the Randall–Sundrum models), Preon theory, combinations of these, or other ideas. Vanishing-dimensions theory is a particle physics theory suggesting that systems with higher energy have a smaller number of dimensions. A third major effort in theoretical particle physics is string theory.

String theorists attempt to construct a unified description of quantum mechanics and general relativity by building a theory based on small strings, and branes rather than particles. If the theory is successful, it may be considered a "Theory of Everything", or "TOE". There are other areas of work in theoretical particle physics ranging from particle cosmology to loop quantum gravity.

In principle, all physics (and practical applications developed therefrom) can be derived from the study of fundamental particles.

In practice, even if "particle physics" is taken to mean only "high-energy atom smashers", many technologies have been developed during these pioneering investigations that later find wide uses in society. Particle accelerators are used to produce medical isotopes for research and treatment (for example, isotopes used in PET imaging), or used directly in external beam radiotherapy. The development of superconductors has been pushed forward by their use in particle physics.

Additional applications are found in medicine, national security, industry, computing, science, and workforce development, illustrating a long and growing list of beneficial practical applications with contributions from particle physics. Major efforts to look for physics beyond the Standard Model include the Future Circular Collider proposed for CERN and the Particle Physics Project Prioritization Panel (P5) in the US that will update the 2014 P5 study that recommended the Deep Underground Neutrino Experiment, among other experiments.

One entry in the Standard Model's roster deserves special mention here because it was the last to be found. The Higgs boson is the particle associated with a field that pervades all space and, by interacting with the other particles, gives many of them their mass; without it, the theory's bookkeeping could not accommodate the observed masses of the weak force's carriers, and the electroweak theory would predict a world unrecognizably different from our own. First proposed in 1964, the particle took nearly half a century to find, requiring the largest machine ever built, and its discovery in 2012 completed the Standard Model's particle census. The mechanism behind it, the field's properties, and the dramatic story of its discovery are the subject of this series' companion volume; in this book it appears where a survey of particle physics needs it, as the theory's crowning entry and the hinge on which the modern era turned.

Chapter 3: Key Characteristics of Particle Physics

Three characteristics fix the field's identity. The first is the dictionary: particle physics alone among the sciences keeps a roster of its objects, the particle data tables, updated every two years with masses, lifetimes, and decay modes, a census now of a few hundred particles and their measured properties, and the roster's refinement is the field's most continuous product, the scorecard against which every theory is tested.

The second is the theoretical spine: everything is quantum field. The field's central doctrine, settled in the twentieth century's middle decades, is that particles are not little balls but localized ripples of fields that fill all space, and that a collision is fields exciting each other into ripples that then disperse as new particles. From this one idea follow the conservation laws, the existence of antimatter, the possibility of creation and annihilation, and the whole of the Standard Model, which is best understood not as a list of particles but as the name for the particular set of quantum fields, with their symmetries, that the universe has been measured to run on.

The doctrine's history is worth one paragraph, because it shows how the field thinks. Quantum mechanics described the particles but not their creation, and the relativistic attempt to fix that produced, at first, infinities and contradictions; the fix, worked out across the 1930s through 1950s, was to promote the fields to primary status and demote the particles to their ripples, and the infinities, absorbed by renormalization into measured constants, became the theory's bookkeeping rather than its failure. The sequence, contradiction, reframing, absorption, verification, is the field's signature maneuver, repeated at every one of its crises, and the reader who learns to recognize it can read the field's whole history as one long repetition of the same honest move.

The field's picture of the vacuum is worth pausing on, because it is the doctrine's strangest fruit. Empty space, in quantum field theory, is not empty: it is the ground state of every field at once, seething with fluctuations, particles borrowed and returned in unobservable instants, and the vacuum itself, in the theory's modern use, is an object with properties, energy density, symmetries, that experiments can approach from several directions. The Higgs field made the point physical: its nonzero value everywhere means the vacuum is not nothing but a medium, and the field's frontier questions, from dark energy to the vacuum's stability, are all versions of one question, what the nothing is actually made of.

The third is the scale gap: the energies at which new physics shows itself are far beyond the laboratory's easy reach, so the field's characteristic patience is structural, not temperamental. Every rung of the energy ladder, from the first cloud chambers to today's colliders, cost a generation's wealth and political will, and the field's practitioners have organized themselves, in collaborations, institutions, and decades-long projects, to match, which is why its characteristics include an odd pair for a basic science: the scale of a public works project, and the bookkeeping of a shipping firm, applied to the smallest objects known.

The field's measuring sticks deserve a closing paragraph, because the units are half the subject's character. Energy is counted in electron volts, the push one electron gains crossing one small battery's worth of voltage, the unit scaling through its thousands and millions and trillions as the machines grew, the field's history legible in its prefixes alone; the cross-section, the physicist's measure of how likely a collision is, is counted in barns, a unit born as a joke in the secret wartime years, the punchline being that a nucleus's target area is as easy to hit as the broad side of a barn, and the joke proved so useful it became official, the field measuring its rarest processes in fractions of a barn so small the fractions need their own exponents. The reader should keep the units' honesty in mind: this is a science that laughs at its own vocabulary, a discipline of trillions of volts and billionths of barns, the extremes of the universe held in a language as comfortable with absurdity as its subject demands.

Chapter 4: The Science Behind Particle Physics

The science beneath the census is quantum field theory, and its logic runs from a few axioms to the whole edifice. Start with the fields, one per particle species; impose the symmetries, which dictate which fields can interact and how; demand that the

quantum mechanics be consistent, which forces the introduction of the force carriers themselves; and the result, after the mathematics is assembled, is the Standard Model, a single equation's worth of structure whose solutions describe every particle and every collision yet observed.

The Standard Model's technical core is worth naming, because its tools are the field's lingua franca. The theory is written in Lagrangians, expressions that list a system's fields and interactions, with the remarkable property that the expression's symmetries dictate its conservation laws; its predictions are computed in Feynman diagrams, the field's iconic stick-figure shorthand for which interactions happen with what amplitude; and its hardest calculations, the ones the theory is famous for, are perturbation series, sums of diagrams that converge to answers like the electron's magnetic strength, computed and measured to agreement in the tenth digit, the most precisely verified prediction in the history of science.

The strong force, described by quantum chromodynamics, is the theory's proudest structural achievement. Its force carriers, the gluons, carry the very charge, color, that they act on, with the consequence that the force does not weaken with distance, and quarks are confined, never seen alone, forever bound into the protons, neutrons, and short-lived hadrons of the census. The same mathematics, run backward to the earliest universe, explains how the protons condensed from the quark-gluon plasma, and the theory's ability to predict, at accelerator temperatures, the observed zoo's masses and lifetimes, is among the most stringent tests any theory of matter has passed.

Quarks carry color, the strong charge, in three varieties, whimsically named red, green, and blue, and hadrons are colorless combinations, red-green-blue trios for the baryons, color-anticolor pairs for the mesons, which is why no free colored particle has ever been seen: the force that confines them grows with distance, so pulling quarks apart costs energy enough to create new quarks, and the attempted escape ends in new colorless pairs instead. The practical consequence for the lab is that the debris of every collision rearranges itself into whole hadrons before it reaches any detector, a fact that shapes every experiment's data analysis.

The weak force supplies the theory's other signature: change. Alone among the forces, the weak interaction can convert one particle into another, a quark into a different quark, a neutrino into an electron's partner, and it is thus the engine of radioactive decay and of the sun's own fusion. Unifying it with electromagnetism, into a single electroweak theory whose different-looking low-energy behavior is a symmetry hidden by the Higgs field, was the Standard Model's decisive construction, and its authors' Nobel Prize the theory's public consecration.

Radioactive decay, the weak force's everyday stage, is worth one more look, because its pace is the force's signature. The weak interaction is weak not because its effects are small but because it is slow, its carrier mass making it rare, and the slowness is why the sun burns for ten billion years instead of detonating, why uranium lasts the age of the Earth, and why the carbon that life is made of was made slowly, in the interiors of dying stars, across the universe's whole history. The field's least glamorous

force, discovered last and named weakest, turns out to be the reason anything has time to happen.

The strangest symmetry deserves the chapter's last word, because the theory's deepest idea is a redundancy. The symmetries the chapter has counted are physical: a turn, a shift, a mirror, things the world itself could do; but the theory's heart is a stranger creature, the local symmetry, a rule that the world's bookkeeping must stay the same even if every point of space chooses its own convention, the way a currency is one economy though every town sets its own rates; and enforcing that freedom of convention, the physicists discovered, requires a field, a messenger, a carrier: the symmetry demands the force. The photon, on this reading, is not a fact bolted onto light but a bookkeeping requirement, the price of letting every point of the universe keep its own gauge; and the reader should hold the idea's audacity as the century's quietest revolution: the forces of nature deduced not from observation but from a demand about consistency, the rulebook of the universe written in the grammar of an accountant's freedom, and every force carrier in the census being, at bottom, a permit for local independence.

Chapter 5: Observation and Measurement of Particle Physics

Particle physics is measured by collision. The instruments of the trade, particle accelerators, speed beams of particles to nearly the speed of light and crash them into stationary targets or, better, into beams coming the opposite way, because head-on collisions pack the maximum energy into the event. What counts is not the violence but the wavelength: to resolve something small, you need a probe with a short wavelength, and energy is wavelength, so every generation of bigger accelerators is a generation of sharper microscopes, looking deeper into matter's structure.

The energy ladder the colliders climb has a history worth retelling in numbers. The first cyclotrons fit in a palm and reached a million electron volts; the machines of the 1950s filled buildings and reached the billions; today's largest ring, twenty-seven kilometers of superconducting magnets under the French-Swiss border, carries beams to over a trillion electron volts, each generation of the ladder a hundredfold gain bought with new physics, stronger magnets, tighter vacuums, superconducting wire. The ladder has a shape the field knows well: exponential for its first half-century, flattening now, and the field's present debate over its next rung is really a debate about the physics of the ladder itself, what acceleration technologies can still be invented.

The collision itself is the easy part; seeing it is the craft. Modern detectors are layered assemblies built like onions around the collision point: innermost, silicon trackers that follow the electrically charged debris through a magnetic field, bending their paths into curves that reveal momentum; then calorimeters that absorb particles and report their energy; outermost, chambers that catch muons, the debris that escapes everything else. Each layer trades a little of the full picture for precision about one

species of particle, and the event's full reconstruction, deciding which tracks belong to which decay, is a mathematical puzzle solved in microseconds, millions of times a second.

The detectors' ancestry is the field's museum of cleverness. The cloud chamber, a supersaturated vapor jar that showed passing particles as threads of droplets, discovered the positron and the muon in its day; the bubble chamber, a superheated liquid that boiled along the particle's track, took over and mapped the strange particles by the thousands; the multiwire chamber, electronics replacing photographs, automated the reading and made the modern flood possible; and today's silicon, grown in the same semiconductor industry that makes phones, tracks particles to microns. Each step traded human eyes for machine speed, and the experiment of the modern era, a hundred million collisions a second, would have been unreadable in any earlier generation.

The computing that tames the collision flood has its own monuments, and the largest is the Grid, the field's answer to a data rate no single site could hold. Collision records stream from the detectors to a Swiss hub and fan outward, to dozens of national centers and hundreds of university clusters, where analysis jobs queue by the thousand, and results return as histograms, the field's universal picture language. The architecture, invented by necessity in the 2000s for the LHC's launch, became the working template for every later large-science computation, and its ancestors, the protocols and practices the field built for the web, show the pattern running: particle physics keeps solving its data problems by building infrastructure the rest of the world adopts.

The bubble chamber era deserves its own sentence of nostalgia, because it was the field's last age of visual truth. A bubble chamber photograph was a picture: the spirals, curves, and forks of a collision, printed and examined by eye, argued over in seminars, and measured by hand, by technicians, and later by machines that learned to trace the tracks' geometry. The photographs' beauty, some now in art books, concealed a brutal lesson, that human eyes could not scale, and their replacement by electronics, which the field completed within a generation, traded the visible for the countable, a bargain the whole of modern science has since made everywhere, but that this field made first.

Statistics is the third leg of the method. Interesting events are rare, so the game is rate times time: collect enough collisions that the faint signature of a new particle, hidden in an immense background of ordinary ones, rises above the noise in the histograms. Discovery in the field is thus an exercise in patience and probability, quantified in standard deviations, with the convention that five sigma, roughly a one-in-three-million fluke, earns the word discovered. The discipline of that threshold, and the worldwide computing grids that tame the flood of data, are as much a part of modern particle physics as any magnet or beam.

The five-sigma convention has a history worth its own sentence. Before the standard, the field had been burned, more than once, by three-sigma bumps that faded with data, particle claims that were not, and the convention, formalized in the era of the

great detectors, is the community's scar tissue: extraordinary claims require extraordinary statistics, and the discipline of announcing only what survives, applied symmetrically to successes and failures, is the field's public covenant with the rest of science.

The measurement chapter should close with the firehose, because the modern experiment's hardest problem is not seeing events but surviving them. A collider's collisions arrive a billion times a second at full flood, and no archive on Earth could hold even an hour of the raw flood; the experiments therefore carry their own triage, layers of electronics that decide, in millionths of a second, which collision is worth remembering and which is noise, the machines trained like old soldiers to keep only the interesting wounds, the overwhelming majority of the universe's most violent events judged, in the instant of their creation, not worth the tape. The reader should hold the triage as the era's defining skill: a generation of experimentalists whose art is not detection but decision, the physics of forgetting built into the instruments themselves, and every discovery of the modern era having passed first through that gate, the filter's designers as responsible for the finds as the collision's makers.

Chapter 6: Important Features of Particle Physics

The Standard Model's features are best remembered as a census and a rulebook. The census: twelve matter particles, six quarks and six leptons, arranged in three generations that repeat the pattern at higher and higher mass for no known reason; a dozen carriers of force: the photon that carries light's own force, the pair of heavy bosons that carry the weak one, the gluons that carry the strong; and one further particle, the Higgs boson, which is not matter and not force but the signature of the field that gives mass its place in the theory. The rulebook: a handful of conservation laws, energy, momentum, electric charge, and a set of bookkeeping charges peculiar to the field, color for the quarks, lepton numbers for the light particles, that govern what can turn into what.

The bookkeeping has produced the field's most practical piece of theory, the conservation-law audit. Every collision, every decay, every proposed interaction is checked against the charges, energy, momentum, angular momentum, electric charge, baryon number, lepton number, color, and the audit's verdicts are absolute: what fails the conservation test does not happen, and what passes is permitted but not guaranteed, with the rates and probabilities supplied by the full quantum mechanics. The proton's stability, the electron's permanence, the sun's long burning, and the impossibility of a perpetual motion machine at any scale are all entries in the same audit, one of the few pieces of paperwork the universe has never been caught misfiling.

The force carriers complete the census with their own personalities. The photon, electromagnetism's carrier, is massless and neutral, which is why its force is long-ranged and why light travels forever; the gluons, eight of them, carry color and glue the nuclei; the W and Z, heavy and short-lived, carry the weak force's slow change; and the theory's bookkeeping says every one of them is a ripple of its own

ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.