SAMPLE

Particle Physics

Quarks, Leptons, and the Standard Model

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Introduction

Particle physics or high-energy physics is the study of fundamental particles and forces that constitute matter and radiation. The field also studies combinations of elementary particles up to the scale of protons and neutrons, while the study of combinations of protons and neutrons is called nuclear physics. The fundamental particles in the universe are classified in the Standard Model as fermions (matter particles) and bosons (force- carrying particles).

There are three generations of fermions, although ordinary matter is made only from the first fermion generation.

The first generation consists of up and down quarks which form protons and neutrons, and electrons and electron neutrinos. The three fundamental interactions that bosons carry are the force of light itself, the feeble changer that works decay, and the binder that holds the nucleus. Quarks form hadrons, but cannot exist on their own. Hadrons that contain an odd number of quarks are called baryons and those that contain an even number are called mesons.

Two baryons, the proton and the neutron, make up most of the mass of ordinary matter.

Mesons are unstable and the longest-lived last for only a few hundredths of a microsecond. They occur after collisions between particles made of quarks, such as fast-moving protons and neutrons in cosmic rays. Mesons are also produced in cyclotrons or other particle accelerators. Particles have corresponding antiparticles with the same mass but with opposite electric charges. For example, the antiparticle of the electron is the positron.

These antiparticles can theoretically form a corresponding form of matter called antimatter. Some particles, such as the photon, are their own antiparticle. These elementary particles are excitations of the quantum fields that also govern their interactions. The dominant theory explaining these fundamental particles and fields, along with their dynamics, is called the Standard Model.

The reconciliation of gravity to the current particle physics theory is not solved; many theories have addressed this problem, such as loop quantum gravity, string theory and supersymmetry theory.

The experimental wing of the field asks its questions in two settings: the radioactive processes, nature's own small machines, and the great colliders built to fling charged particles together at the highest energies industry can

bend to the task. The theoretical wing studies the same census in the contexts of cosmology and the quantum. The two are closely interrelated: the Higgs boson was postulated theoretically before being confirmed by experiments. The idea that all matter is fundamentally composed of elementary particles dates from at least the 6th century BC.

In the 19th century, John Dalton, through his work on stoichiometry, concluded that each element of nature was composed of a single, unique type of particle. The word atom, after the Greek word atomos meaning "indivisible", has since then denoted the smallest particle of a chemical element, but physicists later discovered that atoms are not, in fact, the fundamental particles of nature, but are conglomerates of even smaller particles, such as the electron.

The early 20th century explorations of nuclear physics and quantum physics led to proofs of nuclear fission in 1939 by Lise Meitner (based on experiments by Otto Hahn), and nuclear fusion by Hans Bethe in that same year; both discoveries also led to the development of nuclear weapons. Bethe's 1947 calculation of the Lamb shift is credited with having "opened the way to the modern era of particle physics".

Throughout the 1950s and 1960s, a bewildering variety of particles was found in collisions of particles from beams of increasingly high energy. It was referred to informally as the particle zoo. Important discoveries such as the CP violation by James Cronin and Val Fitch brought new questions to matter-antimatter imbalance. After the formulation of the Standard Model during the 1970s, physicists clarified the origin of the particle zoo.

The large number of particles was explained as combinations of a (relatively) small number of more fundamental particles and framed in the context of quantum field theories. This reclassification marked the beginning of modern particle physics. The current state of the classification of all elementary particles is explained by the Standard Model, which gained widespread acceptance in the mid-1970s after experimental confirmation of the existence of quarks.

The species of gauge bosons are eight gluons, W−, W+ and Z bosons, and the photon. Alongside the force carriers the theory counts its matter: a dozen fundamental fermions, each with its mirror antiparticle, the constituents of everything material. And the theory's boldest prophecy named one particle more, a boson of a new kind, the mass-giver whose hunt would occupy the field's last great decade.

On 4 July 2012, physicists with the Large Hadron Collider at CERN announced they had found a new particle that behaves similarly to what is expected from

the Higgs boson.

The Standard Model, as currently formulated, has 61 elementary particles. Those elementary particles can combine to form composite particles, accounting for the hundreds of other species of particles that have been discovered since the 1960s. The Standard Model has been found to agree with almost all the experimental tests conducted to date.

However, most particle physicists believe that it is an incomplete description of nature and that a more fundamental theory awaits discovery (See Theory of Everything).

A word on the route before the drive begins. The chapters ahead tell the story in the order the century lived it: the discovery chapters set the puzzle and the census; the science and measurement chapters show the method, the machines, and the field's odd units; the modern-understanding chapters assemble the theory and its strangest feature, nature's threefold repetition of its matter recipe; the research and discovery chapters carry the hunt through its great catches and the portraits of the people who made them; and the closing chapters list what remains, where the machines go next, and the trivia that keeps the field human. The account demands no mathematics of the reader beyond plain arithmetic, uses the field's real names sparingly and its units honestly, and reports every result as the experiments reported it; the reader who finishes it will know what the world is made of, how the species found out, and what the finding cost.

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.

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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.