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CAN THE LAWS OF PHYSICS BE UNIFIED?

PAUL LANGACKER

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Physics Be Unified?

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PREFACE

I somehow knew even in high school that I wanted to go into particle physics. Perhaps it was because of Leon Lederman's *Scientific American* article on "The Two-Neutrino Experiment" (Lederman 1963), or perhaps it was because of a series of lectures that I attended in Chicago given by Willie Fowler on nuclear synthesis in the Sun. Whatever the reason, I was hooked. When I began graduate school at Berkeley in 1968, much was already known about the properties of the particles and their interactions. Quantum electrodynamics was well established. Experimentation at ever higher-energy cyclotrons and synchrotrons had discovered large numbers of elementary particles and much about their strong and weak interactions. There were promising theoretical models of aspects of particle physics, but little hope of developing a fundamental mathematical description of the strong or weak interactions in the foreseeable future.[1]

Nevertheless, a revolution in our understanding was about to occur. In less than a decade, the standard model

[1] One of the seminal papers on the standard model had already been published (Weinberg 1967), but was not widely recognized until some years later.

(more properly called the standard theory) of the strong, weak, and electromagnetic interactions was developed and partially confirmed. It did not come out of nowhere, but rather incorporated and synthesized many of the earlier ideas. Over the next 40 years or so, the standard model (extended to include a third family of particles and neutrino mass) was experimentally verified in exquisite detail, culminating in the discovery of the Higgs boson in 2012. It correctly describes nature, at least to an excellent first approximation, in a mathematically consistent way down to a distance scale smaller than $1/1000^{\text{th}}$ the size of the atomic nucleus.

However, the standard model is incomplete. It is simple and elegant in its basic structure, but extremely complicated in detail. It does not fully unify the known microscopic interactions and has many unexplained parameters that must be taken from experiment. It does not incorporate a quantum theory of gravity; explain the observed dark matter and dark energy of the Universe; or account for the excess of matter over antimatter. There are intriguing theoretical ideas for approaching these issues, which however mainly manifest themselves at shorter distances and higher energies than current experiments.

I have been personally fortunate in that my professional career coincided closely in time with the establishment of the standard model. In this volume, I hope to convey some of the wonder and excitement of particle physics, and in the development, implications, and shortcomings of the standard model, as well as to describe something of the theoretical ideas and experimental prospects for the future. It is my hope that sometime in the next 10, 50, or 100 years, we will successfully develop and (at least) indirectly verify an even greater synthesis, which will truly unify all of the interactions, including quantum gravity; perhaps address the origin of space and time; and provide the framework for understanding the large-scale structure, origin, and ultimate fate of the Universe. We may never fully accomplish this dream, but it is a worthy goal.

A Note to the Reader

This book is written for an undergraduate physics student, a practicing scientist in a related field, or any interested reader familiar with the basic ideas of classical physics, quantum theory, and relativity.

Much of the technology in modern particle physics is rather abstract and technical. In order to present the central concepts, problems, and future possibilities at more than a popular level, I have introduced the rudiments of such topics as relativistic quantum theory, Feynman diagrams, and gauge theories. These will be easier for some readers than others, but I hope that anyone with a midlevel undergraduate background in physics will be able to follow enough of the development to appreciate the remainder.

Chapters 1 through 3 should be easily understandable to readers with the stated background. The most challenging parts are sections 4.1 through 4.3, which introduce field theory, internal symmetries, and Yang-Mills theories. I have tried to present the material in such a way that the essential ideas should be accessible even if the mathematical details are not. Sections 4.4

through 4.7 describe our current understanding of the strong and electroweak interactions, the Higgs boson discovery, and neutrino physics. These utilize some of the formalism, but are generally more qualitative and should hopefully be understandable even for readers who have skimmed over the more technical materials. The remaining chapters deal with the problems of the standard model and possibilities for the future. These should be reasonably straightforward.

A confusing variety of terms and acronyms are used in particle physics and cosmology. Most of those relevant here are defined in the extensive glossary, or can be located through the index.

More detailed discussions of particle physics and the standard model can be found in a number of undergraduate (e.g., Griffiths 2008; Mann 2010; Thomson 2013) and graduate (e.g., Langacker 2010; Tully 2011; Quigg 2013) texts. The bibliography contains a mixture of original papers, technical articles, and pedagogical introductions and reviews. The latter are indicated by a double dagger (††) preceding the title.

CAN THE LAWS OF
Physics Be Unified?

1

THE EPIC QUEST

Curious individuals have speculated about nature and humankind's place in it for all of recorded history. The interests of the ancient Greeks included the structure of matter on the smallest scale and that of the Universe on the largest (see, for example, Weinberg 2015). Some of their ideas were surprisingly similar to our modern understanding. Leucippus and his student Democritus proposed in the fifth century BCE an atomic theory in which matter ultimately consists of indivisible atoms that come in various sizes and shapes, accounting for the myriad materials and their properties that we observe. Aristarchus of Samos later proposed a heliocentric cosmology in which the planets rotated around the Sun and the distant stars were similar in character to the Sun. The technology did not exist to test either of these ideas until millennia later, and in fact there were alternative ideas that were more widely believed. Nevertheless, they illustrate the ingenuity and the craving for understanding of the human mind.

The atomic theory was not completely established until the nineteenth and early twentieth centuries, and the understanding of the structure of the atom and of the quantum-mechanical rules that govern its behavior were not fully worked out until some decades later. These ideas, combined with the parallel understanding of electricity and magnetism and of the kinetic theory, form the physical basis for chemistry, electronics, macroscopic matter in all its forms, and even biology.

By the late 1920s, it was known that the atom consists of a cloud of one or more electrons held in place by electrical forces as they orbit a tiny but very massive nucleus. Furthermore, the dynamics are governed not by the venerable classical mechanics of Isaac Newton, but by the weird quantum mechanics according to which electrons seem to be both particles and waves simultaneously. However, this understanding raised many more questions, such as the details of atomic transitions from one level to another. Similarly, what was the nature of the nucleus? Could the different nuclei somehow be composed of protons and electrons? What were the rules that govern the radioactive decays of nuclei that had been observed in the late nineteenth century? How could quantum mechanics, which governs the very small, be combined with Albert Einstein's relativity, which modifies the notions of space and time for rapidly moving observers or in the presence of matter?

Theoretical and experimental developments in the decades surrounding World War II answered some of these questions while raising others. Quantum theory and special relativity were elegantly combined in the Dirac theory and in the quantization of the electromagnetic field. The former predicted the existence of antimatter, which was subsequently observed. The neutron was discovered, and the basic structure of the nucleus as consisting of protons and neutrons held together by a complicated new *strong interaction* were gradually understood. Similarly, the properties of the *weak interaction*, which is responsible for one form of radioactivity (β *decay*) were gradually worked out, and the apparent non-conservation of energy in β decay was finally understood to result from the non-observation of an almost ghostly *neutrino*. The interactions of high-energy particles from cosmic rays or that were artificially accelerated in cyclotrons and subsequent particle accelerators led to the discovery of additional fundamental particles and of systematic properties of their interactions.

These advances led to the new fields of nuclear physics and then of *elementary particle* (or *high-energy*) physics, which sought to systematically understand the properties of the smallest constituents of nature and their interactions. For some 20 years, there was both confusion and painfully slow progress, involving mathematical difficulties in the theories and a proliferation of particles. Finally, however, what we now call the *standard model* (SM) of the elementary particles and their interactions was completed by the early 1970s. In the next 40 years or so, essentially all of the predictions and ingredients of the SM were experimentally verified, often in great detail, the most recent being the discovery of the *Higgs boson* in 2012. The standard model is a mathematically consistent theory that accounts for essentially all aspects of ordinary matter down to a distance scale of $\mathcal{O}(10^{-16}\text{ cm})$.

Despite these successes, the standard model is incomplete: It is very complicated and apparently arbitrary.

The strong, weak, and electromagnetic interactions are very different. Although all are based on the elegant concept of *gauge invariance*, they are not truly unified with each other. A quantum-mechanical description of gravity is not included, although classical general relativity can be grafted on. Furthermore, the SM involves numerous fundamental parameters whose values are not explained. Some of these appear to be fine-tuned to incredibly small (but nonzero) values. There is no explanation of why the electric charges of all particles are integer multiples of $e/3$, where $-e$ is the charge of the electron, nor is there an explanation of the observed excess of matter over antimatter. The neutrinos, initially thought to be massless, are now observed to have nonzero masses much smaller than those of the other fundamental particles. The origin and even nature of these oddball masses are yet to be determined. Finally, the astronomers have determined that the ordinary matter that we are made of and that is described by the SM is only a small fraction of the matter and energy in the Universe. The natures of the dark matter and dark energy are unknown. There is almost certainly a more fundamental desciption of nature that incorporates and extends the SM, generally referred to as *new physics* or *beyond the standard model* (BSM).

There are many ideas for "bottom-up" extensions, with such names as *supersymmetry*, *compositeness*, or *extra space dimensions*, which address some of these issues and which might be manifested in future accelerator and other experiments. "Top-down" ideas, such as *grand unification* or the even more ambitious *superstring* theories could possibly lead to an ultimate unification of the microscopic forces, perhaps including quantum gravity and tackling the origin of space and time. These mainly manifest themselves at incredibly short distance scales that are nearly impossible to directly probe experimentally (with *proton decay* a notable exception), but they might be tested indirectly by their predictions for the low-energy parameters or for new particles or interactions.

There have also been enormous advances since the time of the ancients in our understanding of nature on large scales, including the motions of the Solar System, the composition and energetics of the Sun and stars, of our Galaxy, and of the vast collections of galaxies extending across the fourteen billion light-year radius of the observable Universe.[1] Furthermore, the Universe is expanding and cooling, and can be traced backward to a *big bang* some 14 billion years ago, when it was incredibly hot and dense. Although astronomy and cosmology are not the main thrusts of this volume, they cannot be entirely ignored. The visible parts of stars, galaxies, and other astronomical objects are composed of the same atoms, molecules, nuclei, and elementary particles that we observe in the laboratory, and their dynamics are driven by these particles and their interactions. Even the dark matter is likely due to some still-unobserved elementary particle, while the dark energy may be associated with the ground state (vacuum) energy of some of the fundamental particles. There is even the intriguing suggestion from superstring theory that our observable Universe might

[1] The Universe could be much larger, but we can observe only as far as light has traveled since the big bang.

be but a tiny bubble in a vast *multiverse* of regions, each with different laws of physics! The physics of very small distances and astrophysics/cosmology have become inextricably linked.

The atomic theory and the standard model complete two important chapters in the epic quest begun by the ancient Greeks and others to understand the nature in which we live. Parallel chapters in astronomy include the undertanding of the Solar System, the discovery of galaxies, and the expanding Universe/big bang. Although there have been an enormous range of practical applications (especially of atomic physics) and spinoff technologies,[2] the most important aspect for many is simply curiosity about how nature works at her most fundamental level. The combination of new experimental and observational tools, as well as promising theoretical ideas, gives us the chance of even more exciting chapters yet to come on the very small, the very large, and their relation.

[2]Particle physics has contributed to many important spinoff technologies, including medical diagnostics and therapies, cryogenics, magnet technology, complex electronics, large-scale distributed computing, and the World Wide Web. Mathematical techniques have found application in other branches of physics. Finally, large experiments and labs have been a remarkable model for international cooperation.

2

THE THREE ERAS

2.1 The Ingredients

The description of any physical system requires three ingredients: (1) What are the basic entities to be described? (2) What are the forces or influences acting on them? (3) What are the rules of the game, e.g., how do the entities respond to those influences? For example, Newtonian gravity involves entities such as the Sun, Moon, Earth, apples, or people. The force is gravity, $\vec{F} = G_N m_1 m_2 \hat{r}/r^2$, and the response is given by Newton's laws, especially $\vec{F} = m\vec{a}$. In general relativity, space-time is added to the list of entities, which is distorted by matter, while point masses respond by following geodesics.

The essence of high-energy (particle) physics is the description of nature at the most fundamental level. At our present level of understanding, the basic entities are elementary particles such as *quarks* (constitutents of the proton and neutron) and *leptons* (e.g., the electron and neutrinos). These appear to be *point-like*, i.e., no evidence has been observed for a nonzero size, or that they are composites of still smaller objects or of a continuous distribution of matter.

The quarks and leptons are acted on by at least five types of *interactions*.[1] These are the strong, which binds the quarks and nucleons together; the electromagnetic, responsible for atomic and molecular binding; the weak, responsible for β decay; the *Higgs-Yukawa*, associated with their mass; and the gravitational, which is mainly important for macroscopic objects. These have very different properties. For example, electromagnetism and gravity are long-range, i.e., the forces between two particles fall off slowly with their separation, while the strong interaction between nucleons becomes insignificant for separations much larger than the size of the nucleus. The properties of the known particles and interactions will be described more fully in chapter 3.

The framework is that of relativistic *quantum field theory*, which is the union of quantum mechanics, special relativity, and the possibility of particle creation or annihilation (such as the reaction $e^+e^- \to p\bar{p}$ via an intermediate virtual photon). Our understanding of these issues may eventually be supplanted by something more basic, just as Newtonian gravity was superseded by general relativity.

Another issue is often ignored or taken for granted: are the laws of nature absolute? That is, are they uniquely determined, perhaps by some underlying selection principle or by self-consistency, and are they the same everywhere

[1]The term *interaction* is more appropriate than *force*, in part because interactions can describe particle creation, annihilation, or transitions from one type of particle to another.

in space-time? That is the implicit assumption of most physicists, and we have not seen any conclusive empirical evidence to the contrary. However, developments in superstring theory and cosmology have caused some to question the absoluteness of physics, as will be described in chapter 5.

2.2 Prehistory

One of the precepts of classical physics is absolute space and time. Space is simply the stage on which events occur, and time keeps track of their sequence. They are the same for all observers, and space obeys the flatness axioms of Euclidean geometry. Another cornerstone is determinism: given an exact knowledge of the initial conditions of a system, one can in principle calculate its future evolution. Both of these precepts were shattered in the early twentieth century. Einstein's special relativity of 1905 showed that space and time and even the sequence of events depend on the motion of the observer, while general relativity (1916) showed that space-time need not be flat.

Similarly, quantum theory replaced determinism by uncertainty and probability. We will focus on the wave mechanics formulation, which describes the motion of a particle of mass m moving in a potential $V(\vec{x}, t)$. Instead of the particle following a deterministic trajectory, it satisfies the Schrödinger equation (1926)

$$\left(-\frac{\hbar^2}{2m}\nabla^2 + V\right)\psi = i\hbar\frac{\partial\psi}{\partial t} = E\psi, \qquad (2.1)$$

where the last form refers to an energy eigenstate solution with definite energy E, for which $\psi(\vec{x}, t) = \psi(\vec{x})e^{-iEt/\hbar}$. For negative energies (bound states), only discrete values of E are allowed, i.e., the system is quantized. The wave function $\psi(\vec{x}, t)$ was later interpreted by Max Born as the probability amplitude: $|\psi(\vec{x}, t)|^2$ is the probability of finding the particle at position $\vec{x}$ at time t. Equation (2.1) gives an accurate description of the spectra of hydrogen and other light atoms (after including spin and the Pauli exclusion principle).

After a digression on units, we will turn to the subsequent development of our understanding of particle and nuclear physics, which I divide into the *Era of Exploration*, the *Standard Model Era*, and the *Beyond the Standard Model Era*.

A Digression: Particle Units

Let us briefly digress on *particle units*, $\hbar = 1, c = 1$, a very convenient compact notation useful in particle physics that will be employed in the following. Setting c (the speed of light in vacuum) to unity implies that all velocities are dimensionless quantities expressed as a fraction of the speed of light. It also implies that distance and time have the same units (e.g., a light-second, or just second, is the distance that light travels in one second), and that mass, energy, and momentum all have the same units. Thus, the usual relation $E^2 = \vec{p}^2c^2 + m^2c^4$ between the mass (m), momentum ($\vec{p}$), and energy (E) of a particle becomes $E^2 = \vec{p}^2 + m^2$. Ordinary units can be restored by multiplying a quantity by appropriate powers of $c \sim 3.0 \times 10^{10}$ cm/s, and using the relation $1\ \text{eV}/c^2 \sim 1.8 \times 10^{-33}$ g between grams (g) and electron volts (eV), the energy acquired by an electron accelerated through a one volt potential.[2]

The convention $\hbar = 1$ is motivated by the wave-particle duality of quantum mechanics, and in particular by the de Broglie relation $\lambda = 2\pi\hbar/p$ between wavelength and momentum. Thus, in particle units distance can be expressed in units of energy^{-1} and vice versa. Again, ordinary units can be restored by multiplying by powers of $\hbar \sim 6.6 \times 10^{-16}$ eV-s, and $\hbar c \sim 1.97 \times 10^{-5}$ eV-cm.

It is convenient to introduce the *Planck scale*, $M_P = G_N^{-1/2} \sim 10^{28}$ eV, where G_N is the gravitational constant. Its value $\sim 6.7 \times 10^{-8}\text{cm}^3\,\text{g}^{-1}\,\text{s}^{-2}$ becomes $6.7 \times 10^{-57}\,\text{eV}^{-2}$ in particle units. Its significance is that the coefficient of $1/r^2$ in the Newtonian force law is the dimensionless ratio $m_1 m_2/M_P^2$. Gravity becomes strong for masses (or energies in the generalization to general relativity) of $\mathcal{O}(M_P)$, and quantum gravity effects then become important.

Particle units emphasize that in some sense, c and $\hbar$ are not really fundamental quantities, and the conventional values are observable only due to the historical accidents about how such units as g, s, cm, and eV were defined. Only dimensionless ratios such as v/c, the fine structure constant $\alpha = e^2/4\pi$, and ratios of particle masses to each other or to the Planck scale are physically meaningful.

[2]Related energy units, such as GeV, are defined in the glossary.

2.3 The Era of Exploration

The era of exploration refers to the development of particle physics prior to the standard mode. The period spans roughly from the quantization of the electromagnetic field[3] by Paul Dirac in 1927 to the development of the *electroweak* $SU(2) \times U(1)$ *model* (late 1960s) or the development of *quantum chromodynamics* (QCD) (early 1970s).

Field quantization refers to the replacement of a quantum wave function or a classical field by an operator that contains creation and annihilation operators. Similar to those of the simple harmonic oscillator, these act on a quantum state to obtain a state involving respectively one more or one less particle or quantum of the field. For each frequency $\omega/2\pi$, direction, and polarization of the electromagnetic field, for example, there can be an integer number of quanta (*photons*), each carrying energy $\hbar\omega$, i.e., ω in particle units. Field quantization allowed a description of atomic transitions involving the emission or absorption of a photon.

The Dirac equation (1928) is a relativistic wave equation for a spin-1/2 particle. Remarkably, this union of special relativity with quantum mechanics predicted the existence of antimatter, i.e., the Dirac equation for the electron had additional solutions corresponding to a positively charged particle. After some confusion that this particle might be the proton, it became clear that it had to have

[3]Detailed discussions of the history are given in Pais (1986) and Weinberg (1995).

the same mass as the electron. The existence of this anti-electron, now known as the *positron* (e^+), was confirmed in 1932 by Carl Anderson's observation of positron tracks from cosmic rays in a cloud chamber.

Quantum electrodynamics (QED) was developed experimentally and theoretically in the subsequent two decades or so (see, for example, Schwinger 1958). QED, which involves quantized Dirac and electromagnetic fields, combines classical electrodynamics, quantum mechanics, and special relativity. It explains subtleties such as the Lamb shift in hydrogen and the anomalous magnetic moment of the electron. Early on, QED exhibited seemingly insuperable mathematical difficulties involving infinities encountered in summing over intermediate states in perturbative calculations. By around 1950, however, it was understood that these infinities could be cured by *renormalization* theory, in which physical observables are expressed in terms of the measured values of quantities such as mass and charge rather than the parameters in the original equations of motion.[4] QED is mathematically consistent down to incredibly small distance scales, and has now been tested at the precision of 10^{-8}–10^{-9} in many experiments. It is generally spectacularly successful, although in recent years two anomalies, possibly due to new physics, have emerged. These will be described in chapter 4.

In parallel with the development of QED, the 1930s witnessed significant progress in understanding the structure of the nucleus and the nature of the strong

[4]The modern view is that the infinities never really appear, since sums over intermediate states are truncated by, e.g., the Planck scale, $M_P \equiv G_N^{-1/2}$.

interactions. Already by 1920, Ernest Rutherford had speculated that atomic nuclei might consist of protons and what he termed "neutrons," which however consisted of a proton and electron that were somehow much more tightly bound together than were nuclei and atomic electrons. This was economical in terms of particle content,[5] but soon ran into difficulties as the ideas of quantum mechanics were developed. For example, the observed nuclear sizes and binding energies conflicted with the Heisenberg uncertainty relation, and the model required that the ^{14}N nucleus should have half-integer spin, while molecular spectroscopy indicated that it has spin-1.

These difficulties evaporated with James Chadwick's discovery of the neutron in 1932, which has spin-1/2 rather than the integer spin of Rutherford's bound state. The modern view of the nucleus as consisting of tightly bound protons and neutrons was quickly accepted. Heisenberg and others postulated what is now called *isospin* or $SU(2)$ symmetry. This was the first appearance of an *internal symmetry*, a notion that was central to later developments in particle physics. It implies that the strong interactions of the proton and neutron (known collectively as *nucleons*) are closely related and that they would have the same mass in the absence of electroweak interactions, which do not respect the symmetry.[6]

In 1934, Hideki Yukawa wrote his first paper on what is now called the *Yukawa theory* of the strong interaction.

[5]This is an early instance of the reluctance of physicists to invent new particles.

[6]It is now understood that the quark mass differences also contribute to isospin breaking.

The idea was that the strong force is mediated by the exchange of a massive electrically charged *meson*, leading to a pn potential $V(r) \propto g_\pi^2 e^{-m_\pi r}/r$, where g_π is the p-n-meson coupling and m_π is the meson mass. The force can therefore be large for small distance, but falls off rapidly with r, with range $R = 1/m_\pi$. From the observed $R \sim 1$ fm $= 10^{-13}$ cm, Yukawa estimated $m_\pi \sim 200\, m_e$, where $m_e \sim 0.511\,\text{MeV}$ is the electron mass. A few years later, a charged particle with roughly that mass was observed in cosmic rays. However, it gradually became clear that it was not Yukawa's particle, but is actually the *muon* ($\mu^\pm$), a heavier carbon copy of the $e^\pm$. Yukawa's particles, now known as *pions* ($\pi^\pm$), were finally observed in cosmic rays in 1947, and a third electrically neutral π^0 in 1950. They have spin-0 but couple to nucleons as pseudoscalars rather than scalars. The charged pions have mass $m_{\pi^\pm} \sim 270\, m_e$ but are much lighter than the proton mass, $m_{\pi^\pm} \sim 0.15\, m_p$. They decay to the somewhat lighter $\mu^\pm$ and a neutrino by weak interactions, and the π^0 to 2γ electromagnetically. Including heavier mesons discovered later, the appropriately modified Yukawa potential gives an approximate description of the long-range part of the nuclear interaction. Unfortunately, attempts to turn the Yukawa interaction into a full-fledged field theory in the 1950s were not very successful. Unlike QED, which can be expanded perturbatively in the fine structure constant $\alpha = e^2/4\pi \sim 1/137$, the Yukawa interaction is very strong. The analog of α is $g_\pi^2/4\pi = \mathcal{O}(10)$, so that perturbative calculations are not very meaningful.

In addition to the pions, heavier mesons, now known as *kaons* ($K^\pm$, K^0, $\bar{K}^0$), with masses intermediate between the pions and nucleons, were observed to be produced in cosmic ray interactions. Heavier versions of the nucleons (the *hyperons*) were discovered somewhat later. These had the surprising property that they could be produced rapidly by strong interactions, but decayed very slowly, even when there were final states such as $K^+ \to \pi^+\pi^0$ that could presumably be reached by strong processes. The resolution, due to Murray Gell-Mann, Kazuhiko Nishijima, and others, was that these new particles carry a new quantum number, dubbed *strangeness* ($\mathcal{S}$), which is conserved by the strong interactions. Ordinary pions and nucleons have $\mathcal{S} = 0$, but the strange particles can be produced strongly by the *associated production* of an $\mathcal{S} = 1$ particle, such as K^+ or K^0, and an antiparticle with $\mathcal{S} = -1$, such as K^- or $\bar{K}^0$, e.g., $\pi^0 p \to K^+ \bar{K}^0 n$. However, the $K^+ \to \pi^+\pi^0$ decay would violate strangeness[7] and can proceed only by the much more feeble weak interaction, which does not conserve $\mathcal{S}$.

The muons and strange particles did not seem to play any essential role in nature.[8] These were the first observations of particles from a heavier *family*, the role of which is still not fully understood.

Over a hundred additional strongly interacting particles (known as *hadrons*) were discovered at particle accelerators during the 1950s and 1960s, causing Enrico Fermi to remark "If I could remember the names of all these particles, I'd be a botanist." Much was known empirically about their properties and interactions. They had

[7] Strange particle decays also violate isospin.

[8] The muon discovery led Isidor Rabi to make his famous remark, "Who ordered that?"