Dramatic Changes in Physics Since 1952

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Elementary-particle (note the hyphen) physics is the study of the fundamental particles and forces of nature. Since we entered high school, the knowledge and definition of the elementary particles and fundamental forces of nature has changed dramatically.

Of course there have been many other developments in physics during this period that affected our daily life, such as integrated circuits (the heart of the personal computer and nearly everything else), the maser (precision atomic clocks → global positioning system, GPS), the laser (surgery, product scanner, DVD player), light emitting diodes (LED), liquid crystal displays (LCD), medical imaging (computer aided tomography (CAT), magnetic resonance imaging (MRI), positron emission tomography (PET), ultrasound), synchrotron light sources (the highest brightness X-rays), not to mention the World Wide Web (not physics, but developed at a particle-physics lab, CERN in Geneva, SZ, for physicists working on experiments from far-flung locations), but none of these developments changed our fundamental understanding of nature as has the discovery that matter as we know it is composed of quarks and gluons interacting via four (actually three, possibly two) fundamental forces. We now call this the 'Standard Model' (of particle physics), so named by Sheldon Glashow, BXHSS'50, with major contribution from Steven Weinberg, BXHSS '50, for which they shared the Nobel Prize in Physics, in 1979, together with Abdus Salam of Pakistan and Britain.[1]

When we entered Bronx Science in 1951 or 1952, the known elementary particles were:

[1] You may remember that our physics teacher, Dr. Herman Gewirtz, attended our 25^{th} reunion at the automat. I asked him whether he had Steve Weinberg as a student and he told me, "In fact I had *two* Steve Weinbergs as students. Which one won the Nobel Prize?"

the photon, the quantum of electromagnetic energy invented by Einstein in one of his three seminal 1905 papers whose anniversary we celebrate this year; the proton and neutron (collectively nucleons), which make up the atomic nucleus; the electron which orbits the nucleus to give us chemistry and the periodic table of the elements (and also electricity, electromagnetic radiation, electronics...); the positron, the anti-particle of the electron, which can annihilate with an electron to produce photons—the annihilation of matter with anti-matter to produce pure energy according to Einstein's famous $E = mc^2$. All of these particles, save the positron, make up the matter of which everything in our experience is composed: the Earth, its inhabitants, the solar system, and, believed until recently, the whole universe. There were also two very short-lived (< 2.2 μ-second) particles of mass between the electron and the much more massive proton, hence dubbed mesons, the μ-meson (muon) and the π-meson (pion). These had been discovered in cosmic rays, the energetic particles which rain down on us from outer space and interact in the atmosphere. There were also a few "strange" particles, which appeared as isolated 'V's in cosmic ray interactions in photographic emulsions exposed on high mountains or in balloon flights.

The science of particle physics changed dramatically in the early 1950's with the advent of particle accelerators able to accelerate protons to energies greater than 2 Billion (now giga) electron-Volts (GeV), roughly twice the energy equivalent of the rest mass of the proton.[2] Hence, there was enough energy to produce a proton-antiproton pair, if all the kinetic energy of the accelerated proton could be dissipated in a collision. In fact, the anti-proton was discovered at the new 6 GeV Bevatron at Berkeley in 1955, the year we graduated from high school (and is now the subject of a rather amusing book by Dan Brown, *Angels and Demons*), but this was expected. Much more interesting was the unexpected 'zoo' of new particles that were also produced.

In general, the field of elementary particle physics proceeded for the past 50 years as in the example above: a new accelerator opened up a new range of available energy (or type of accelerated particle, e.g. colliding beams of positrons and electrons), and coupled with new detector technology—which enabled improved or previously impossible measurements to be made—rapidly yielded discoveries soon after it started up. In 1953, when a new 1 GeV

[2] An electron-volt (eV) is the energy gained by a particle with electric charge equal to that of an electron crossing a potential difference of 1 volt.

electron accelerator was built at Stanford University, Robert Hofstadter (CCNY) was able to make precision measurements of the radii and shape of atomic nuclei. While Rutherford, in 1911, had observed that the positive charge in atoms was all located in a tiny nucleus (later found to be composed of protons and neutrons), Hofstadter was the first to find that an elementary particle, the proton, had a finite size, with a radius of 0.8 fm (femto-meters, 10^{-15} m = 10^{-13} cm). By comparison, to this day, no size has been observed for an electron—its radius is less than 10^{-18} cm, the present limit of measurement resolution.

On very general principles, the higher the energy of the probe, the smaller the distance probed. This is why elementary-particle physics is also called High Energy Physics. For the past 50 years the energy (and size) of accelerators has steadily increased until the cost is now beyond the ability of any single country or region to afford, and we discuss the "Next Linear Collider" or NLC as a world project. The situation was different in the 1950's when construction of the 30 GeV Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL, where I did my PhD thesis and where I now work) was approved following a 1 page proposal to the AEC, and a similar accelerator was built at the new European Laboratory for Particle Physics, CERN, in Geneva, Switzerland. When these accelerators started operation in the 1960's, a zoo of new particles was discovered, enabled by the development of the hydrogen bubble chamber and the first computer processing of photographs. These new technical developments also allowed the Bevatron at Berkeley to remain in the game.

Soon thereafter, in 1962, M. Gell-Mann and Y. Ne'eman proposed that all particles sharing common quantum numbers[3] follow the symmetry of mathematical group theory, in particular the group SU(3). This led Gell-Mann to predict the existence of a new Baryon (massive, like a nucleon), the Ω^-, with strangeness quantum number= -3, spin=3/2, charge=-1, which was observed in 1964 at BNL by Nick Samios (Stuyvesant, Columbia) with mass charge and strangeness as predicted. Gell-Mann (and Zweig), in 1964 then noted that the SU(3) symmetry was based on 3 elementary generators, which he called "quarks", which were considered merely mathematical entities from which the properties of the known particles could be reconstructed. Gell-Mann's 3 quarks were u, d, s, for up, down, sideways (or

[3] Elementary particles are classified by properties called quantum numbers which are conserved in reactions. The "strange" particles were assigned their own quantum number called "strangeness".

strange), with fractional charges (in units of the magnitude the electron charge) $+2/3$, $-1/3$, $-1/3$:

$$\begin{array}{r|ll|} +2/3 & u & \\ -1/3 & d & s \end{array} \quad .$$

and *e.g.* a proton is composed of uud.

One problem with this model was that the Ω^- had 3 identical s quarks in the same state, apparently violating the Pauli Exclusion Principle. To avoid this problem, it was proposed (only half facetiously) that perhaps quarks come in 3 different 'colors' which would allow several otherwise identical quarks to occupy the same 'wave function'.[4]

Meanwhile, back at Stanford, W. K. H. Panofsky was building an even bigger electron accelerator, the 30 GeV, 2 mile long (Stanford) linear accelerator, SLAC. In 1968, shortly after the accelerator began operating, Kendall, Friedman, Taylor and Bjorken discovered that electrons appeared to scatter off pointlike structures inside the proton, which Richard Feynman dubbed 'partons' to indicate that the proton was made up of smaller parts. The same effect was observed in proton-proton collisions in 1972 at the new Intersecting Storage Ring (ISR) colliding beam machine at CERN. A huge number of mesons came out with large momentum at right angles to the collision, indicating that the partons interacted much more strongly with each other relative to the electromagnetic scattering observed at SLAC. Independently of these measurements, in 1970, Shelly Glashow proposed a fourth quark, c, with charge $+2/3$ which he named "charm", to explain, by symmetry. the absence of a certain decay mode of strange particles:

$$\begin{array}{r|ll|} +2/3 & u & c \\ -1/3 & d & s \end{array} \quad .$$

Then, in 1974, in a truly momentous event, called "the November revolution", Sam Ting at the BNL AGS and Burt Richter at Stanford[5] simultaneously discovered a quasi-stable (i.e. relatively long-lived) particle, the J/Ψ, with roughly double the mass of any known particle. The slow decay implied a new conservation law. The J/Ψ was quickly understood to be a bound state of heavy c-$\bar{c}$ quarks—the hydrogen atom of QCD (see below). Suddenly

[4] Formally (O. W. Greenberg), quarks are para-fermions of order 3.

[5] Richter used a new machine, SPEAR, an electron-positron collider, while Ting made the discovery 15 years after the startup of the AGS!

all physicists believed in the reality of quarks as the 'partons', the fundamental constituents of the proton.

I have described only the elementary particles. There is a similar story regarding the forces by which the particles interact. In modern terms a force is the result of the exchange of 'quanta'. (For instance, the photon, also called γ, is the quantum of the electromagnetic force.) The two major discoveries were: 1) Glashow, Weinberg, Salam—that the electromagnetic force and the Weak force, which causes radioactive decay, are just two facets of the same interaction, now called Electro-Weak and mediated by the exchange of 4 'quanta' (also called Bosons), γ, $W^{\pm}$ and Z^0; 2) Gell-Mann and also Gross, Wilczek and Politzer (BXHSS), in 1973—that the the real SU(3) symmetry is not the original u, d, s quarks but the 3 colors, which are the coupling-constants (like electric charge) of the strong (or nuclear) interaction, the force that holds all the positively charged protons in a nucleus from breaking apart. The exchanged quanta of this force are color-charged gluons and the theory is called Quantum Chromo Dynamics, QCD, which exhibits 'asymptotic freedom' (2004 Nobel Prize)—the quarks and gluons interact freely at short-distances by the exchange of gluons, but are confined i.e unobservable at separations greater than the radius of a nucleon. The 'type' of quark, u, d, s, c, is now called 'flavor' and it turns out that there are actually 6 (delicious) flavors of quarks, including the b or bottom quark (1977) and the recently discovered t or top quark (1994) , an elementary particle roughly 200 times more massive than the proton, indicating that there is still much to be learned.

Fifty years of elementary-particle physics in $\sim$1000 words is a challenge. I've tried to outline some of the results and excitement. The details, for those interested, are spelled out in some popular references below (you can just type the book titles into Google or Amazon and click, thanks to the WWW) and in the attached wall chart. You can even buy the chart as a ready made place mat. I guess that indicates how far we have come!

What was it like to be part of all this?

The committee asked me to describe what it was like to be part of all this. My answer is that while it was happening it didn't seem out of the ordinary since I came to expect the highest intellectual standards, rigor and curiosity from my Bronx Science and later Columbia education. Also, many of the players were either from Bronx Science or from Columbia or from New York City, so were familiar types, even if you'd just met them for the first time.

In retrospect, the enlightened view of the U.S. government in supporting us to pursue this 'curiosity driven' basic research into the fundamental properties of matter and energy, and the successes we achieved, are truly astounding. It was interesting, challenging, and, to be frank, fun, although at times it was very tedious and difficult. The payoff in terms of our understanding of nature can not be quantified in monetary value, but the intellectual rigor, the quantitative methods, the high level of technology, the knowledge and application of science and the spinoffs have been the driving forces of our present 'information' and 'technology' economy.

Perhaps the committee wanted to know what I did in all this. It's given on my web page (address in the heading), which, I note, hasn't been updated since 1999. Since then, I've been working on the PHENIX experiment at RHIC, the Relativistic Heavy Ion Collider at BNL, a machine—consisting of two superconducting rings of magnets—which smashes gold nuclei together to obtain the hottest, densest matter which has existed in the universe since the big bang. There is lots of excitement and we have been making lots of discoveries. Fortunately, the matter we produce is different from and much more interesting than what was originally predicted. On April 18, 2005, a big press conference will be held at the American Physical Society meeting, so hopefully when you read this, you'll have seen some recent coverage of our results in the press.

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[1] *"Surely You're Joking, Mr. Feynman": Adventures of a Curious Character*, Richard P. Feynman, *et al.*

[2] *The Second Creation: Makers of the Revolution in 20th Century Physics*, Robert C. Crease and Charles C. Mann.

[3] *Inward Bound: Of Matter and Forces in the Physical World*, Abraham Pais.

[4] *Nobel Dreams: Power, Deceit, and the Ultimate Experiment*, Gary Taubes.

[5] *The God Particle: If the Universe is the Answer, What Is the Question?*, Leon M. Lederman.

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

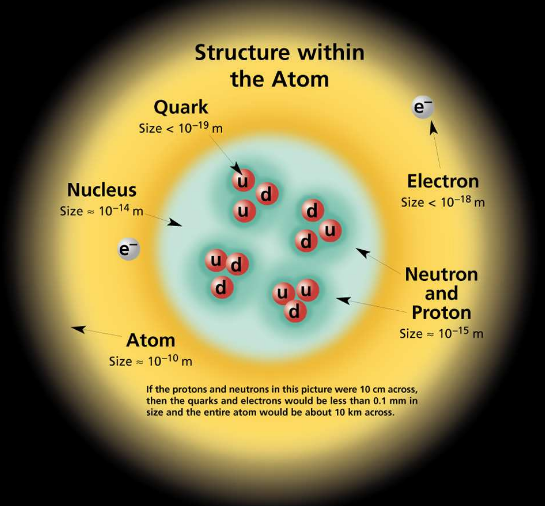
Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV $= 10^9$ eV $= 1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 $= 1.67\times10^{-27}$ kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$ — Baryons are fermionic hadrons. There are about 120 types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$ — Mesons are bosonic hadrons. There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

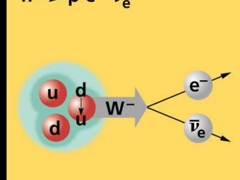
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

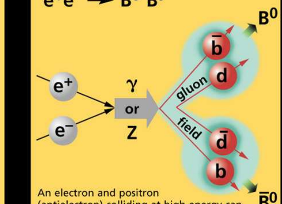
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



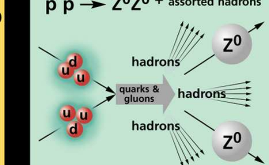
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\, p \rightarrow Z^0 Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at **http://ParticleAdventure.org**

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