Quarks, Leptons and the Forces of Nature

A Quick History of and Introduction to Particle Physics

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International Particle Physics Outreach Group

INTERNATIONAL MASTERCLASSES
hands on particle physics

NUI MAYNOOTH
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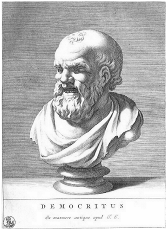
Introduction

Mankind has always known the universe was made of "stuff". But what is the "stuff" itself made of? And why do we care?

- A Scientific Reason: Because we want to know what the actual nuts and bolts of the universe are, and how and why they fasten together in the way they do.
- A Philosophical Reason: By knowing what makes up the rest of the universe, we learn about what we ourselves are made of and how we might fit into the big picture.
- A Practical Reason: Knowing how the universe itself is put together may help us create new means and technologies to better our lives.
- A Selfish Reason: Because we enjoy doing it!

Leucippus and Democritus (c. 400 BCE)



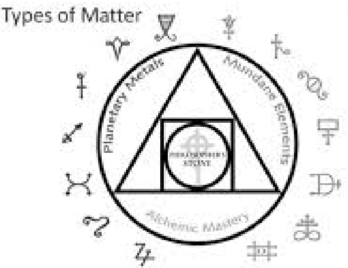
"Matter is *not* infinitely divisible!"

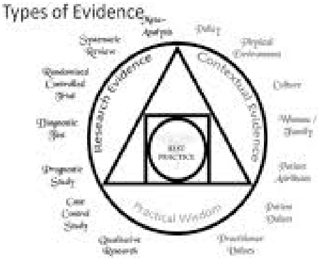
$\alpha\tau o\mu o\zeta$ – *atomos*, "uncuttable"

But it didn't catch on, so the basic idea of fundamental bits of matter fell out of favour for over two millennia...

Alchemy

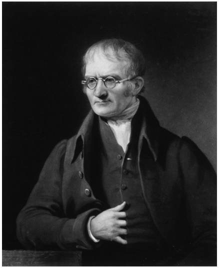
...but the idea of "basic building blocks" of the universe was still popular.

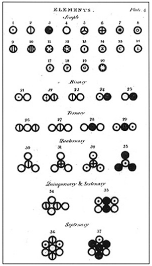




All objects are made of different combinations of fundamental substances, and this determines their properties.

John Dalton (1805)



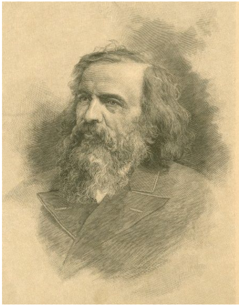


Atoms were revived as the fundamental pieces of matter, with the added idea that there were a finite number of kinds classified by their *weight*.

The Periodic Table

Dmitri Mendeleev (1869)

When elements were also grouped according to their chemical properties, the periodic table was born.



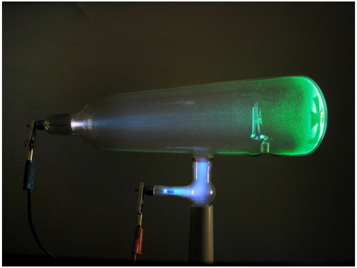
Group → / Period ↓	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

But were these "new" atoms really indivisible?

The First Subatomic Particle

J. J. Thomson (1889)

Heating the cathode in a Crookes tube lead to the emission of rays of *electrically-charged* particles.

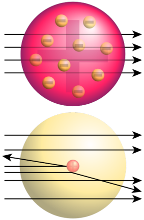


Thomson determined these rays had negative charge, and in 1891, Irish physicist George Stoney named them *electrons*.

The Nucleus

Ernest Rutherford (1909, 1920)

The positive charge in an atom was *not* evenly distributed, but concentrated in the centre: the nucleus.



This charge was bound up in particles he named *protons*. The rest of the mass of the nucleus was theorised to be due to undiscovered neutral particles, and in 1932, *neutrons* were found.

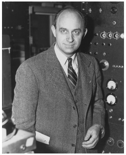
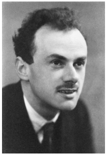
The New Physics

These new particles were very, very small and could move very, very fast. Luckily, two new theories covered both...

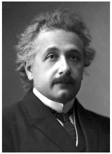
- *Quantum Mechanics* gave a new description of physics at extremely small length scales, explaining the structures of atoms and molecules.
- *Special Relativity* explained the phenomena that occurred when physics took place near the speed of light, and pointed toward deep connections between mass, energy and momentum.

Although bizarre and counterintuitive to many of the world's best scientists, the two theories were astoundingly successful.

When combined, the two theories predicted a new fundamental property of matter (like mass and electric charge), which comes in chunks of 1/2 and divides all matter into one of two types:

spin = 1/2, 3/2, 5/2, . . .
Fermi-Dirac particles, or *fermions*

spin = 0, 1, 2, . . .
Bose-Einstein particles, or *bosons*

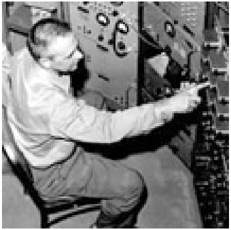
Another prediction was that every fermion had a near-exact duplicate, differing only in the sign of its electric charge. These new particles were called *antimatter*.

The first of these antiparticles to be found was the counterpart to the electron, the *positron* e^+. The antiproton $\bar{p}$ and antineutron $\bar{n}$ followed in 1955 and 1956.

Carl Anderson (1932)

A Mysterious New Particle

When neutron decay – into a proton and electron – was observed in 1934, the energy didn't add up: the total energy of the final particles was *less* than that of a neutron. The proposed solution? A third particle with zero mass and charge was being produced; a "little neutral one", or in Italian, *neutrino*.



The very-hard-to-detect neutrino wasn't found until over 20 years later!

Clyde Cowan and Frederick Reines (1956)

The Particle "Zoo": Things Get Messy...

As detectors and accelerators got more sophisticated in the '30s, '40s and '50s, more and more particles were discovered...

- Baryons (large masses, spin 1/2, 3/2, ...):
  n, p, Λ, Σ, Ω, Δ, Ξ, ...
- Mesons (medium masses, spin 0, 1, ...):
  π, ρ, K, $\bar{K}$, η, ϕ, ω, ...
- Leptons (small masses, spin 1/2):
  e^-, ν_e, μ^-, ν_μ, ...

I. I. Rabi, on the muon: "Who ordered *that*?"

The Zoo Explained: Quarks and Leptons

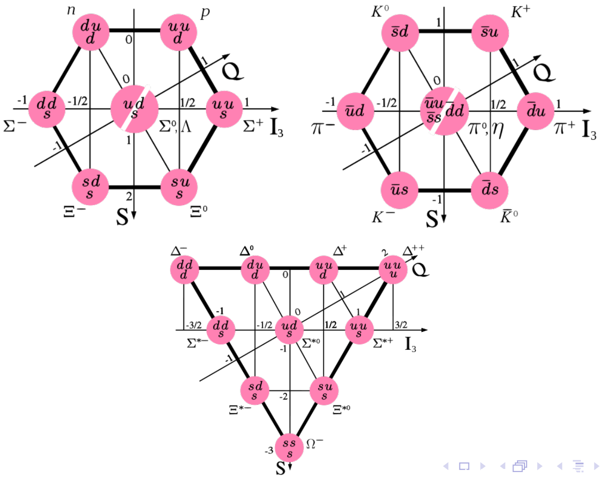
Murray Gell-Mann and George Zweig (1964)

The fundamental particles of matter are all fermions: the well-known leptons (electrons, neutrinos, etc.) plus a new type, *quarks*, where

- baryons are made of three quarks;
- mesons are made of a quark and an antiquark.

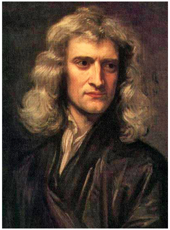
New "Periodic Tables"

The three most common quarks – the up, down and strange – can combine according to these rules to group the most common baryons and mesons into natural families:



What is a Force?

Newton's Second Law (1687)



"The alteration of motion is ever proportional to the motive force impress'd; and is made in the direction of the right line in which that force is impress'd."

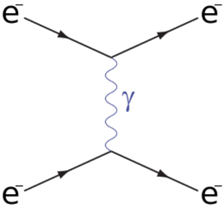
In other words,

$$\vec{F} = m\vec{a}$$

A force causes a mass to change *speed* and *direction*. How does this work at the subatomic level?

Forces as Particle Exchange

By a process of photon emission and absorption, two electrons can repel each other, as illustrated by a *Feynman diagram*.



All forces are due to an exchange of special particles called *gauge bosons*; the photon is the gauge boson which "carries" the electromagnetic force.

So forces are now described as *interactions* that determine which particles can absorb, emit, combine with or decay into each other.

Conservation Laws

Allowed interactions are restricted by *conserved* quantities, whose total sum after the interaction must be the same as before. Apart from familiar quantities like energy, momentum and angular momentum, there are other "quantum numbers" which are always conserved:

- Electric charge Q
- Baryon number B
- Lepton number L
- Weak isospin T_3

Other quantum numbers are sometimes conserved, sometimes not, depending on the interaction involved: for example, strangeness S.

Quantum Numbers

leptons

	Q	B	L	T_3	S
e^-	-1	0	$+1$	$-\frac{1}{2}$	0
ν_e	0	0	$+1$	$+\frac{1}{2}$	0
μ^-	-1	0	$+1$	$-\frac{1}{2}$	0
ν_μ	0	0	$+1$	$+\frac{1}{2}$	0
τ^-	-1	0	$+1$	$-\frac{1}{2}$	0
ν_τ	0	0	$+1$	$+\frac{1}{2}$	0

quarks

	Q	B	L	T_3	S
u	$+\frac{2}{3}$	$+\frac{1}{3}$	0	$+\frac{1}{2}$	0
d	$-\frac{1}{3}$	$+\frac{1}{3}$	0	$-\frac{1}{2}$	0
c	$+\frac{2}{3}$	$+\frac{1}{3}$	0	$+\frac{1}{2}$	0
s	$-\frac{1}{3}$	$+\frac{1}{3}$	0	$-\frac{1}{2}$	-1
t	$+\frac{2}{3}$	$+\frac{1}{3}$	0	$+\frac{1}{2}$	0
b	$-\frac{1}{3}$	$+\frac{1}{3}$	0	$-\frac{1}{2}$	0

(To get the quantum numbers for the antileptons and antiquarks, simply flip the signs!)

The Four Forces, Part I: The Electromagnetic Interaction

- Felt by all particles with electric charge
- Responsible for atomic and molecular structure and the chemical properties of elements
- Manifests as visible light, radio waves, microwaves and X-rays
- Carried by the photon γ, a massless neutral spin-1 boson

Example: electron-positron annihilation into two photons, $e^- + e^+ \to \gamma + \gamma$

The Four Forces, Part II: The Strong Interaction

- Felt by all particles composed of quarks and antiquarks (called *hadrons*)
- Responsible for nuclear structure
- Does *not* become weaker as the distance between quarks increases
- Carried by the gluon g, a massless neutral spin-1 boson.

Example: creation of a neutral pion from a proton-proton collision, $p + p \rightarrow p + p + \pi^0$

The Four Forces, Part III: The Weak Interaction

- Felt by all matter and antimatter
- Responsible for neutron decay and β-radiation
- The shortest-ranged of the four forces; negligible at distances larger than a nucleus
- Carried by three heavy spin-1 bosons, the neutral Z and the charged W^+ and W^-

Example: neutron decay into a proton, electron and electron-antineutrino, $n \to p + e^- + \bar{\nu}_e$
(and a few more examples to come...)

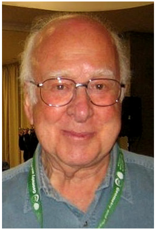
The Four Forces, Part IV: The Gravitational Interaction

- The most familiar of the four forces; felt by all known particles
- Responsible for planets, stars and galaxies
- At short distances, the weakest of the four forces; utterly negligible at subatomic scales
- The only force which has not been successfully explained using quantum mechanics
- Hypothesised to be carried by a massless, neutral spin-2 boson, the graviton

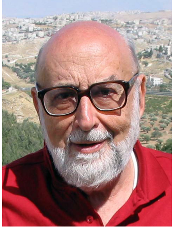
Example: none known yet at a subatomic level, but many known at planetary scales and larger

The Question of Mass

Peter Higgs and François Englert (1964)



Higgs and Englert proposed a process by which fundamental particles interact with a boson which "slows them down" as they travel through space, giving them an inherent mass: the *Higgs mechanism*.

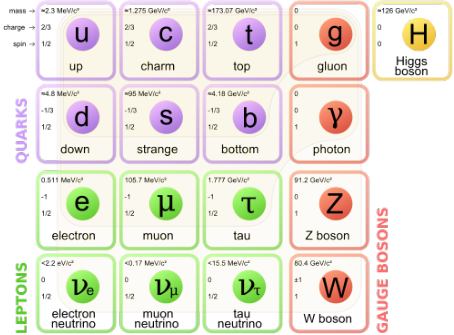


The discovery of a heavy, neutral spin-0 particle which seems to play this role was announced by CERN in 2012; it is thought to be this elusive "Higgs boson", H.

The Standard Model

The most successful and comprehensive theory of fundamental particles and forces that physics has yet thought of...

The Particles



The Interactions

Electromagnetism
Strong Force
Weak Force
Higgs Mechanism

Of Particular Interest to Us: Z and Higgs Decays

The ATLAS detector at CERN looks for the following decays after colliding two beams of protons together, all of which involve either a Z-boson or Higgs boson...

- Z-boson decay:

$$Z \to e^+ + e^- \quad \text{or} \quad Z \to \mu^+ + \mu^-$$

- Higgs boson decay:

$$H \to t + \bar{t} \to \gamma + \gamma \quad \text{or} \quad H \to Z + Z \to \ell^+\ell^- + \ell^+\ell^-$$

where ℓ signifies an electron or muon.

A Few Pluses and Minuses of the Standard Model

Good:

- In terms of explaining past observations and making testable predictions, one of the most successful scientific theories ever
- Explains why electromagnetism and the weak force seem to be intimately related to one another: the *electroweak interaction*

Less Good:

- Many of the parameters describing the interactions seem arbitrary and have to be put in by hand
- Requires neutrinos to be massless, despite experimental evidence that they do, in fact, have mass

Some Current Questions in Particle Physics

- Can a theory which includes both quantum mechanics and the gravitational force be found? String theory and loop quantum gravity claim so, but no evidence for either yet.
- The evolution of the universe points toward the existence of "dark matter" and "dark energy". What are they? New forms of matter and energy, or old ones in disguise?
- Electromagnetism and the weak force seem to be different aspects of the same interaction; is the same true of the strong force? Is there a "grand unified theory" that combines them all?
- Why is there so much more matter than antimatter in the universe? What is the theoretical reason for this profound asymmetry in the makeup of the universe?
- And finally...

When will Ireland join CERN?

Thank you!