

Particle Physics

CERN Lectures

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Recommended Books and Resources

There are a number of textbooks and semi-popular books that hit roughly the right level. First the semi-popular:

- Tini Veltman, “*Facts and Mysteries in Elementary Particle Physics*”

A straightforward book describing the essentials of the particle physics with some historical anecdotes thrown in for colour. Veltman won the Nobel prize with Gerard 't Hooft for demonstrating the renormalisability of the Standard Model.

- Abraham Pais, “*Inward Bound*”

A spectacularly detailed book, covering discoveries in particle physics throughout the 20th century by a scientist who had a ringside seat for many of the key developments. Pais was no slouch as a physicist, providing important classification schemes for particles, naming both “baryons” and “leptons” and, with Gell-Mann, the first to understand the mixing of neutral kaons. On the flip side, he also coined the wildly inappropriately modest name “The Standard Model”. (And he didn’t even capitalise it.)

- Leon Lederman, “*The God Particle*”

To get anything out of this book you first have to get past the appalling title and then past the grating voice in which every story is buried neck deep in wisecracks, delivered with the all the subtlety of a dinner party bore after a line of cocaine. Still, given that Lederman is one of the great experimental particle physicists of the past century, it is sometimes worth the effort.

If you want more mathematical meat, then there are a few books that require a knowledge of quantum mechanics but fall short of using the full machinery of quantum field theory. Two good ones are:

- Halzen and Martin, “*Quarks and Leptons*”
- David Griffiths, “*Introduction to Elementary Particles*”

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Acknowledgements

Every summer, [CERN plays host](#) to a cohort of university students from around the world. The students come from a range of backgrounds, from theoretical and experimental physics, to computing, engineering and mathematics. They spend the summer working on some of the CERN experiments, while taking a number of crash courses designed to get them up to speed with the CERN mission.

These lecture notes form the introduction to the CERN course. They cover the basics of particle physics and are designed to be accessible to students with any scientific background. This means that, despite the advanced topics, the notes require significantly less mathematical sophistication than my [other lecture notes](#). Sadly there is a price to be paid, and this comes in the form of facts. Lots and lots of facts. But particle physics is a subject where it helps to know what you're getting yourself into before you meet the somewhat daunting mathematics. These lectures should hopefully give you a flavour of what awaits in more detailed courses.

1 Introduction

The purpose of these lectures is to address one of the oldest questions in science: what are we made of? What are the fundamental building blocks of the universe from which you, me, and everything else are constructed?

In the twentieth century, progress in addressing this question was nothing short of spectacular. By the time the dust had settled, we were left with a remarkably simple picture: every experiment that we've ever performed can be explained in terms of a collection of particles interacting through a handful of forces. The theory which ties all of this together is the pinnacle of 350 years of scientific endeavour. It is, by any measure, the most successful scientific theory of all time. Yet we give it a rubbish name: it is called the *Standard Model*.

These lectures have two, intertwined narratives. The main thread describes the contents and structure of the Standard Model. The language in which the Standard Model is written is known as *quantum field theory*, and much of our initial focus will be on describing this framework, and the way it forces upon us certain inescapable facts about the universe. As we proceed, the emphasis will be on the key theoretical ideas that underpin the Standard Model and more detailed descriptions of the particles and the forces that make up our world.

Many of the ideas that we will meet are abstract and counterintuitive and they took physicists many decades to understand. It is striking that, at nearly every step, what ultimately lead physicists in the right direction was experiment. Sometimes these experiments simply confirmed that theorists were on the right path, but more often they came as a surprise, forcing physicists in entirely new directions.

The second thread of these lectures is to describe these experimental advances, and attempt to connect them to the more theoretical ideas. With this goal in mind, each chapter ends with an accompanying “Interlude” in which we take a more historical tour through the subject, describing some of the key experimental results, along with some of the confusions that plagued the physicists of the time.

Finally, it is clear that the Standard Model is not the last word, and we will see what questions it fails to answer. In the last section we raise some of the outstanding open problems and speculate a little on what lies beyond.

In the remainder of this extended introduction, we will give a whirlwind tour of the Standard Model, painting the big picture by omitting many many details. As these

lectures progress, we will fill in the gaps. Much of the theory sits on an excellent footing, in the sense that we now know that some aspects of the laws of physics could not be any different: many details are forced upon us by mathematical consistency alone. In contrast, other parts of the theory remain mysterious and it is unclear why the world appears one way, rather than another.

The Structure of the Atom

Before our forefathers understood atoms, or nuclei, or elementary particles, they understood chemistry. And this is where our story starts.

Our modern, scientific understanding of the structure of matter begins with the chemist John Dalton and his “law of multiple proportions”. This is the observation that, when mixing elements together to form different compounds, you should do so in integer amounts. So, for example, you can combine carbon and oxygen to form one type of gas, but if you want to make a different type of gas then you need exactly double the amount of oxygen.

That’s surprising. It’s not, for example, what happens when you bake. If you’ve discovered the perfect recipe for sourdough, then you don’t double the amount of flour and suddenly find that you’ve got bread for a bagel. That’s not the way things work. Dalton understood the importance of his observation which he interpreted, correctly, as evidence for the old ideas of Leucippus and Democritus who argued that matter is made of indivisible objects called atoms.

These days, the idea of atoms is sewn into the names that we give to the gases. Add carbon and oxygen in equal measure and you get carbon monoxide CO . Double the oxygen and you get carbon dioxide CO_2 . But there’s no such thing as $\text{CO}_{\sqrt{2}}$ because you can’t have $\sqrt{2}$ oxygen atoms attached to each carbon atom.

A fuller picture came with Mendeleev’s arrangement of the elements in the pattern known as the periodic table. In 1867, he placed the elements in (roughly) order of their mass, grouped together based on their observed properties. Mendeleev realised that the gaps in his table were opportunities, rather than flaws: they were elements that were yet to be discovered. In this way, he predicted the existence of germanium, gallium and scandium. It would not be the last time that a theorist was able to predict the existence of a new, seemingly fundamental, particle.

From the perspective of a chemist, the periodic table is important because it places elements in groups with similar behaviour. Those elements on the left of the table go fizz when you put them in water. Those on the right don’t. However, from the perspective

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	57 La *	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	89 Ac *	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
				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	71 Lu	
				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	103 Lr	

Figure 1. The periodic table of elements. (Image from [Wikipedia.](#)) We can now do better.

of fundamental physics, the importance of the periodic table can be found in the clues it gives us for what lies beneath. By Mendeleev’s time, it had long been understood that elements are made of atoms. The name atom was optimistically derived from the Greek “atomos”, meaning “indivisible”. The order in the periodic table suggests a structure to the atoms. The elements are labelled by two numbers. The atomic number Z is an integer and tells where the atom sits in the table. The atomic weight A tells us the mass of the atom and, for the first few elements in the table, is very close to an integer. We now know that both of these numbers have their origin in the fact that atoms are very much divisible.

Concrete progress came in 1897 when JJ Thomson discovered the particle that we now call the electron. He announced the discovery to a stunned lecture room at the Royal Institution in London. Thomson later recalled that one of the distinguished scientists in the audience told him that he thought the whole thing was a hoax.

It took another 35 years to unravel the full structure of the atom, with much of the work done by Ernest Rutherford and his colleagues. By the time the dust had settled, it was clear that each atom consists of a nucleus, surrounded by a somewhat blurry cloud of electrons. The nucleus itself is comprised of two further particles, the proton and neutron. The atomic number Z counts the number of protons in the nucleus; the atomic weight A counts (roughly) the combined number of protons and neutrons.

The electrons carry electric charge. By convention, the charge is taken to be negative, an annoying choice that you can blame on Benjamin Franklin, one of the founding fathers of the US. The protons carry positive charge. The neutrons are, as their name suggests, neutral. Remarkably, but importantly, the magnitude of the charge of the proton is exactly the same as the electron; they differ only in sign. Atoms contain an equal number of electrons and protons and so are themselves neutral.

The nucleus sits at the heart of the atom, but is tiny in comparison. Atoms have a typical size of 10^{-10} m, while the nuclei have a typical size of 10^{-15} to 10^{-14} m. Rutherford himself used the analogy of a fly in the centre of a cathedral. Despite its small size, the nucleus contains nearly all the mass of the atom. This is because the protons and neutrons are much heavier than the electron. We will learn more about the properties of particles later, but for now we'll just mention that the mass of the electron is

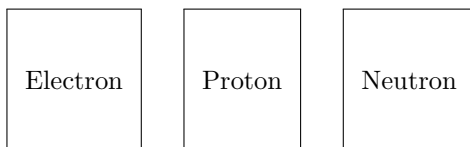
$$m_{\text{electron}} \approx 9.1 \times 10^{-31} \text{ kg}$$

(The kilogram is a useful unit when weighing humans. Less so for elementary particles. We'll meet a better unit shortly.) Both the proton and neutron are roughly 2000 times heavier. Or, more accurately,

$$\begin{aligned} m_{\text{proton}} &\approx 1837 m_{\text{electron}} \\ m_{\text{neutron}} &\approx 1839 m_{\text{electron}} \end{aligned}$$

The fact that the masses of the proton and neutron are so close remains something of a mystery. As we will later see, it is related to the fact that two smaller particles called quarks have almost negligible masses but this, in turn, is not something that we can explain from more fundamental arguments. Nonetheless, the approximate equality $m_{\text{proton}} \approx m_{\text{neutron}}$ is important and is the reason that the atomic weights A are so close to integers for the light elements. For now, these numbers simply tell us that the electrons contribute less than 0.1% of the mass of an atom.

The story above paints a much simpler picture of the structure of matter than that proposed by Mendeleev. At the fundamental level, the complicated periodic table can be replaced by something significantly simpler. It would appear that we need just three particles to explain the elements. They are:



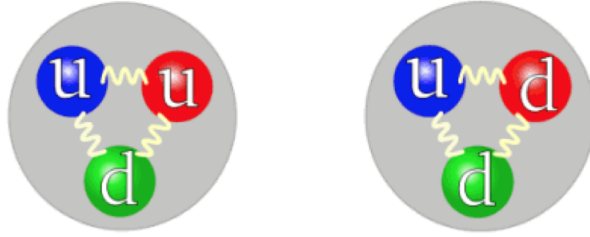


Figure 2. The proton, shown on the left, contains two up quarks and a down quark. The neutron, shown on the right, contains two down and an up.

Sadly physicists had less than 100 days to enjoy this simple picture! The neutron was the last of the three particles to be discovered. That happened in May 1932. In August of the same year, anti-matter was found and subsequent discoveries then came thick and fast. We now know that the sub-atomic world contains many riches beyond the three obvious particles that can be found in atoms.

The Structure of the Structure of the Atom

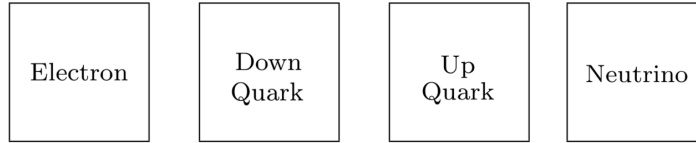
The history of how we understood the structure of matter is long, complicated and confusing and will be told in part as these lectures progress. But, at first blush, the end result seems to be not much more complicated than that of the rosy picture that scientists had in early 1932. For all we can tell, the electron remains as a fundamental particle. In contrast, neither the proton nor the neutron are fundamental. Each contains smaller particles known as quarks. A cartoon version (we’ll do better later) says that the proton and neutron each consist of three quarks that, in turn, come in two different varieties. They are called the *up quark* and the *down quark*. The names are not particularly evocative: there is nothing “up” nor “down” about either of the quarks.

The proton contains two up quarks and a down quark, while the neutron contains two down quarks and an up. Both quarks have fractional electric charge. In units in which the electron has charge -1 , the up quark has charge $+\frac{2}{3}$ and the down quark charge $-\frac{1}{3}$. This then gives the familiar charges of the proton ($\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$) and the neutron ($-\frac{1}{3} - \frac{1}{3} + \frac{2}{3} = 0$).

In addition, there is a further, neutral particle called the *neutrino*. This is not one of the building blocks from which we’re made but, as we shall see, has an important role to play in the universe. The neutrino carries no electric charge and is much lighter than all the other particles. It is usually introduced with the epithet “elusive”: it barely

interacts and can travel through a lightyear of lead with only a 50% chance of hitting anything.

This, then, leaves us with our new periodic table, a world with just four particles:



One might have thought this was a good place to stop. However, at this stage, something strange happens. For reasons that we don't understand, Nature chose to take this pattern of four particles and repeat it twice over. The total number of particles of this type that we know about in the Universe isn't 4, but 12.

In addition to the electron, there are two further particles. They behave like the electron in every possible way. For example, they have the same electric charge and, as we will see later, the same interactions with other forces. The only way in which they differ from the electron is that they're heavier. They are called the *muon* and the *tau* (pronounced to rhyme with “now”). They have masses

$$m_{\text{muon}} \approx 207 m_{\text{electron}}$$

$$m_{\text{tau}} \approx 3483 m_{\text{electron}}$$

Similarly, there are two extra neutrinos and four extra quarks. The neutrinos inherit their name from the corresponding electron-like particle: we talk of “electron neutrinos” and “muon neutrinos” and “tau neutrinos”. The quarks in the second group are called *strange* and *charm*. There was a brief time when physicists toyed with the idea of naming the third group of quarks *beauty* and *truth*. The latter was subsequently rejected out of a well-placed sense of embarrassment, but the names that remain in their place, *bottom* and *top*, are astonishingly dull¹. This, then, is the final pattern of particles that we find ourselves with:

¹Nearly everyone now refers to the b quark as bottom. One exception is LHCb, an important experiment at CERN devoted to the study of b quarks. They prefer the older name, presumably because they would rather be LHC-beauty than LHC-bottom. The obvious suggestion that they embrace both names and rebrand themselves LHCbb has gone sadly unheeded.

Electron 1	Down Quark 9	Up Quark 4	Electron Neutrino $\sim 10^{-6}$
Muon 207	Strange Quark 186	Charm Quark 2495	Muon Neutrino $\sim 10^{-6}$
Tau 3483	Bottom Quark 8180	Top Quark 340,000	Tau Neutrino $\sim 10^{-6}$

The numbers in the table are the masses of the particles, written as multiples of the electron mass. (Hence the electron itself is assigned mass 1.) The masses of the neutrinos are known to be very small but, otherwise are only constrained within a window and not yet established individually.

Each horizontal line of this diagram is called a *generation*. Hence, each generation consists of an electron-like particle, two quarks, and a neutrino. The statement that each generation behaves the same means that, among other things, the electric charges of all electron-like particles in the first column are -1 (in appropriate units); the electric charges of all quarks in the second column are $-\frac{1}{3}$ and all those in the third column $+\frac{2}{3}$. All neutrinos are electrically neutral.

We understand aspects of this horizontal pattern very well. In particular, various mathematical consistency conditions tell us that the particles must come in a collective of four particles, and their properties are largely fixed. In particular, we understand why the particles have the electric charges that they do: this is forced upon us by the mathematics and they simply can't be anything else. We'll describe this more in Section 4.

We don't, however, understand the observed pattern of masses. More importantly, we don't understand the vertical direction in the pattern at all. We don't understand why there are 3 generations in the world and not, say, 17. Nonetheless, we know from both particle physics and from cosmological observations that there are no more than 3 light neutrino species and measurements of the way the Higgs decays tells us that it

doesn't couple to anything heavier than the top. It seems likely that we're stuck with these three generations and nothing else.

The 12 particles listed above are all the “matter particles” that we have so-far discovered in the universe. Each has some fairly intricate properties that we will learn as these lectures progress. In particular, each particle has a corresponding anti-particle, and both the particles and anti-particles decompose further into “left-handed” and “right-handed” pieces. We will describe all this in Section 2.

Forces

All the particles that we described above interact through a handful of forces. It's usually said that there are four fundamental forces at play in the universe. In fact, by any logical count, we should say that there are five forces, with the interaction of the Higgs boson providing the fifth.

The traditional four forces of Nature are:

- Gravity: This was the first force to be discovered and, in many ways, the one we understand least. The effects of gravity are very familiar: it's the reason why apples fall from trees and tides wash in and out. It's the reason why planets orbit stars, and stars form galaxies, and the reason why these are all dragged inexorably apart by the expansion of the universe. Our best theory of gravity was given to us by Einstein: it is the theory of [General Relativity](#).
- [Electromagnetism](#): Like gravity, this force is familiar because it manifests itself in the macroscopic world, where it is harnessed for much of modern technology. On the atomic level, it is the electromagnetic force, acting between the electrons in an atom, that give rise to the chemical properties of the elements.
- Strong Nuclear Force: This force has no counterpart in classical physics. It is responsible for binding quarks together inside protons and neutrons and, subsequently, for binding protons and neutrons together as nuclei.
- The Weak Nuclear Force: Another force that manifests itself only on very small scales. Its primary role is to allow certain particles to decay into other particles. For example, beta radiation, in which a neutron decays into a proton, electron and anti-neutrino occurs because of the weak force.

The story above contains a little bit of a lie. At the fundamental level (meaning at the shortest distance scales), the force of electromagnetism should be replaced by

something called *hypercharge*. It's not dissimilar to electromagnetism, but it differs in details. What we observe as electromagnetism is some mix of hypercharge and the weak force.

Finally, the “fifth force” is:

- The Higgs Force: Again, a force which has no classical analog. Its role, however, is rather dramatic: it allows all the elementary particles described in the table above to get a mass.

Each of these five forces will be described in considerable detail as the lectures progress. Section 2 describes the matter particles and their interaction with electromagnetism; Section 3 describes the strong force; and Section 4 describes the weak force and the Higgs boson. Finally, we will turn to gravity in Section 5.

1.1 Quantum Fields

Ironically, the theory of particle physics is not a theory of particles. It's a theory of *fields*. A field is a fluid-like object which is spread throughout all of space. A field can take a different value at every point in space, and that value can change with time.

The most familiar examples are the electric and magnetic field which are associated to the electromagnetic force. These comprise of a pair of vectors, which exist at every point in the universe. Mathematically, the electric and magnetic field are functions $\mathbf{E}(\mathbf{x}, t)$ and $\mathbf{B}(\mathbf{x}, t)$, which can take different values at different points \mathbf{x} in space and points t in time. Like all fluids, the electromagnetic field can ripple. These ripples are what we call light waves.

Things get more interesting when we introduce quantum mechanics into the mix. In the 1920s, physicists understood that, on the smallest distance scales, the universe doesn't follow the common sense laws that Newton gave us. Instead, it's much more mysterious and counter-intuitive, and follows the rules of quantum mechanics. One of the key consequences of quantum mechanics is that energy isn't something smooth and continuous. Instead, energy can only be parcelled in discrete lumps. That's what the word “quantum” means: discrete, or lumpy.

The real fun happens when we try to combine the ideas of quantum mechanics with fields. One implication is that the electromagnetic waves that make up light are not continuous. Instead light is made up of particles called *photons*. The photons are ripples of the electromagnetic field tied into little parcels of energy due to quantum mechanics.



Figure 3. This is not what physicists mean by a field. It’s what a farmer means by a field. Or a normal person.

The surprise is that the paradigm above holds for all other particles too. First, each of the forces described above has a field associated to it. And, when quantum mechanics is taken into account, ripples of the field become particles. The names of the particles associated to each of the forces are:

- Electromagnetism: As described above, the particle is the photon. In particle physics, photons are denoted by the greek letter γ (gamma). This comes originally from high-energy photons known as “gamma rays”, but is now used to describe photons of any energy.
- Strong Nuclear Force: The field associated to this force is called the *Yang-Mills field*. The corresponding particles are *gluons*.
- Weak Nuclear Force: The field is another variant of the Yang-Mills type. The corresponding particles are the *W and Z bosons*.
- The Higgs Force: The associated particle is called, unsurprisingly, the *Higgs boson*. It was discovered at CERN in 2012, the last of the Standard Model particles to be found experimentally.
- Gravity: The force of gravity is rather special. Einstein’s theory of general relativity teaches us that the gravitational field is actually space and time itself. Ripples of space and time are called *gravitational waves* and were first observed by the LIGO detector in 2015. The associated quantum particles, known as *gravitons*, have not been observed experimentally. Given the weakness of gravitational interactions, it seems unlikely that this situation will change any time soon.

So each force is associated to a field and an associated quantum particle. But, so too, are the matter particles. For example, spread throughout the room you're sitting in, and in fact throughout the entire universe, there exists something called the electron field. The ripples in this fluid get tied into little knots, or little bundles of energy, by the rules of quantum mechanics. And those bundles of energy are the particles that we call electrons. Every electron is a ripple of the same underlying field, like waves are ripples of the same underlying ocean.

There is also a muon field, and a tau field, together with six different kinds of quark fields and three kinds of neutrino fields. The Standard Model of particle physics is a theory describing how 12 matter fields interact with 5 fields of force. If one field — say the electron field — starts to move and sway, then it causes the gravitational field and the electromagnetic field to move. These, in turn kickstart the quark fields, and so on. All of these fields are engaged in an intricate, harmonious dance, swaying backwards and forwards, to a music that we call the laws of physics.

This can be contrasted with our view of classical physics. There we have two very different objects: particles and fields. At times, they make fairly awkward bedfellows. But there is a beautiful unification in the quantum world: everything is field. The particles are emergent objects.

The Implications of Quantum Fields

The world of quantum fields can, at times, be difficult to get our heads around. It is often easier to resort to the language of particles and, for the most part, this is what we will do in these lectures. Nonetheless, there are times when the particle picture breaks down and it is only when we think in terms of fields that things make sense. Here we describe a number of implications of the field theoretic picture. We'll see many more as the lectures progress.

Implication 1: First, and most importantly, field theories allow us to write laws of physics consistent with locality. If you shake an electron, it doesn't immediately affect a second electron sitting elsewhere. Instead the shaking electron produces a perturbation in the neighbouring electromagnetic field. This then propagates outwards, until it reaches the second electron. In this manner, there is no “action-at-a-distance”, and causality is ingrained in the very structure of field theory.

Implication 2: The second consequence of quantum fields is the following: all particles of a given type are the same.

For example, two electrons are identical in every way, regardless of where they came from and what they've been through. The same is true of every other fundamental particle. Suppose, for example, that we capture a proton from a cosmic ray which we identify as coming from a supernova lying 8 billion lightyears away. We compare this proton with one freshly minted in a particle accelerator here on Earth. And the two are exactly the same! How is this possible? Why aren't there errors in proton production? How can two objects, manufactured so far apart in space and time, be identical in all respects? The answer is that there's a sea of proton "stuff" that fills the universe. This is the proton field or, if you look closely enough, the quark field. When we make a proton we dip our hand into this sea and mould a particle. It's not surprising that protons forged in different parts of the universe are identical: they're made of the same stuff.

Implication 3: The field perspective allows us to simply interpret situations where the number of particles changes. For example, beta decay is a process in which the neutron decays,

$$n \rightarrow p + e + \bar{\nu}_e$$

The decay products are a proton p , and electron e and an electron neutrino $\bar{\nu}_e$. (The bar on the $\bar{\nu}_e$ tell us that it's actually an anti-neutrino; we'll describe anti-matter in Section 2.) In terms of the underlying quarks, the down quark decays into an up quark

$$d \rightarrow u + e + \bar{\nu}_e$$

From a particle perspective, this is somewhat confusing. You might be tempted to view the decay above by thinking that a proton, electron and anti-neutrino are sitting inside the neutron, perhaps bound together by some mysterious force and just waiting to get out. (Or, equivalently, that the down quark is made of an up quark, electron and anti-neutrino.) But that's *not* the right way to think about the neutron (or the down quark.) Indeed, we've stated above that the down quark is a fundamental constituent of matter, and that would be difficult to believe if it contained other objects.

Happily, these confusions evaporate when we think in terms of fields. The particle that we call the down quark is a ripple of the down quark field. But there's no reason to think that this ripple can last forever. Instead, it can decay, but only at the cost of exciting three other fields: those of the up quark, electron and neutrino. The reason why these three particular fields get excited, and no others, is due to the detailed interactions of the various fields. These rules will be described as these lectures progress.

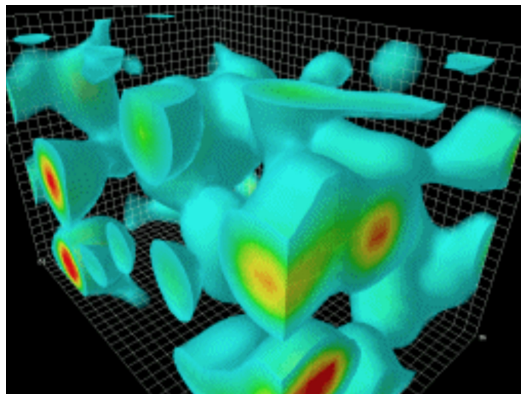


Figure 4. The vacuum of space is an interesting and complicated place. This picture is taken from the QCD simulation of [Derek Leinweber](#)

Implication 4: There is one last idea that will be useful to have in the back of your mind: the existence of quantum fields means that empty space, also known as the vacuum, is not a dull place. It is filled with quantum fields which, even when left alone, are not necessarily calm. An example is shown in Figure 4, depicting a computer simulation of empty space. What’s shown is a typical configuration of the gluon field in the vacuum. The true vacuum is, in fact, much more complicated even than that shown in the picture. The vacuum doesn’t have just a single field configuration but is something more murky: a quantum superposition of infinitely many different field configurations, each appearing with some probability. In quantum field theory, the vacuum of space is an interesting place. It froths with quantum uncertainty.

The take-home message for these lectures is that the vacuum of space is not some inert, boring substance. The bubbling fields breathe life into the vacuum and mean that it is able to respond to things happening within it. This phenomenon, as we shall see, lies at the heart of some of the more subtle effects of quantum fields.

1.2 Natural Units

Before we get going, we should introduce the units that we use to quantitatively describe the sub-atomic world. Usually in physics, we introduce different units for length, time and mass. For example, the SI units are meters, seconds and kilograms respectively. However, at the fundamental level these concepts are not as different as they first appear and the laws of physics provide a way to translate between them.

For example, there is a speed limit in place in the universe. No particle can travel faster than

$$c = 299792458 \text{ ms}^{-1} \approx 3 \times 10^8 \text{ ms}^{-1} \quad (1.1)$$

All particles with mass are obliged to travel slower than this speed, while all massless particles are obliged to travel at exactly this speed. The most familiar massless particle is the photon and for this reason c is referred to as the speed of light.

The speed of light allows us to translate freely between units of length and units of time. Given a length scale L , there is a natural time scale $T = L/c$, which is the time it takes light to cross the distance L .

In fact, the existence of a constant speed in the universe is hinting at something deeper: the concepts of space and time are not as distinct as we first thought. To put this in perspective, here's an analogy. I might decide that I'm going to measure all horizontal distances in centimeters, and all vertical distances in inches. I then proudly reveal a new fundamental constant of nature C which translates between the two,

$$C \approx 0.394 \text{ Inches cm}^{-1}$$

This is clearly a dumb thing to do. If I have a ruler marked in cm to measure horizontal distances, then I can always rotate it and use it to measure vertical distances in cm as well. The rotational symmetry in the world means that there is no fundamental difference between distances in the horizontal and vertical directions.

But exactly the same story holds for the speed of light. The theory of special relativity tells us that there is a symmetry between space and time, albeit one that only becomes apparent when you travel fast. If you move close to the speed of light you experience strange effects like time dilation and length contraction, which can be explained by a rotation of time into space and vice versa. What this means is that, at the fundamental level, we should measure time and space using the same units. If we choose to measure time in seconds, then we should measure length in light-seconds, the distance that light travels in a second. With this choice, the speed of light is simply

$$c = 1$$

A corollary of this is that mass is now measured in the same units as energy. This is because Einstein's famous formula $E = mc^2$ becomes simply $E = m$. In these lectures, we will specify the masses of elementary particles in units of energy. If, for some reason, you want to get the mass in, say, kilograms, then you simply need to reinstate the factor of the speed of light in $m = E/c^2$ and use the value $c \approx 3 \times 10^8 \text{ ms}^{-1}$.

A similar story arises when we consider quantum mechanics. The fundamental constant in quantum mechanics is Planck's constant,

$$\hbar = 1.054571817 \times 10^{-34} \text{ Js}$$

It has units of energy \times time. What this constant is really telling us that, at the fundamental level there is a close connection between energy and time. A process with energy E will typically take place in a time $T = \hbar/E$. In this way, we can translate between units of energy and units of time, and these concepts are not as distinct as our ancestors believed. To highlight this, we choose units so that

$$\hbar = 1$$

The choice $c = \hbar = 1$ is referred to as *natural units*. It means that there's only one dimensionful quantity left, which we usually take to be energy. Any measurement — whether it's of length, time or mass — can be expressed in terms of energy.

A Sense of Scale

The SI unit of energy is a Joule and is not particularly appropriate for the sub-atomic world. Instead, we use the electronvolt (eV) which is the energy an electron picks up when accelerated across 1 volt. This is

$$1 \text{ eV} \approx 1.6 \times 10^{-19} \text{ J}$$

The electronvolt is the energy scale appropriate for atomic physics. For example, the energy that binds an electron to a proton to form a hydrogen atom is $E \approx 13.6 \text{ eV}$. For elementary particles, we will need a somewhat larger unit of energy. We typically use $\text{MeV} = 10^6 \text{ eV}$ or $\text{GeV} = 10^9 \text{ eV}$. The LHC, our best current collider, runs at an energy scale measured in $\text{TeV} = 10^{12} \text{ eV}$. (It's worth pointing out that this is actually closer to a Joule than it is to an electronvolt!)

The masses of the 12 matter particles cover a range from eV to GeV. They are:

Electron 0.5 MeV	Down Quark 4 MeV	Up Quark 2 MeV	Electron Neutrino < 0.1 eV
Muon 106 MeV	Strange Quark 87 MeV	Charm Quark 1.3 GeV	Muon Neutrino < 0.1 eV
Tau 1.8 GeV	Bottom Quark 4.2 GeV	Top Quark 170 GeV	Tau Neutrino < 0.1 eV

The entries for neutrinos are upper bounds on the mass. Meanwhile, the masses of the 5 force-carrying particles are

Photon massless	Graviton massless	Gluon ~ 200 MeV	W and Z Bosons 80, 91 GeV	Higgs Boson 125 GeV
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For each of these particles, there is an associated length scale. We get this by transforming energy E into a length using the fundamental constants of Nature c and \hbar ,

$$\lambda = \frac{\hbar c}{E} \tag{1.2}$$

This is known as the *Compton wavelength*. Roughly speaking, it can be viewed as the size of the particle. For example, for the electron the Compton wavelength is $\lambda_e \approx 2 \times 10^{-12}$ m. Perhaps somewhat surprisingly, the heavier a particle is, the smaller its Compton wavelength.

The Biggest and the Smallest

There are two further length scales that we should mention before delving into details of the subatomic world. One is associated to the strength of the gravitational force. Newton's constant is given by

$$G_N \approx 6.67 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$$

In natural units, Newton’s constant has dimensions of [Energy]⁻². Putting back the factors of \hbar and c , we can derive an energy scale known as the Planck mass

$$M_{\text{pl}} = \sqrt{\frac{\hbar c}{8\pi G}} \approx 2 \times 10^{18} \text{ GeV}$$

(The factor of 8π is conventional, and is sometimes dropped.) This is an enormous energy scale, fifteen orders of magnitude larger than the scales that appear in the Standard Model. The corresponding length scale is the Planck length

$$L_{\text{pl}} = \sqrt{\frac{8\pi\hbar G}{c^3}} \approx 8 \times 10^{-35} \text{ m}$$

This, in turn, is a tiny length scale, 15 orders of magnitude smaller than the scale that we have explored at our best particle colliders. The Planck scale is where both quantum mechanics and gravity become important. It seems likely that space and time cease to make sense at these scales, although it’s not clear exactly what this means.

On the other end of the spectrum, the largest size that we can talk about is the entire observable universe,

$$L_{\text{universe}} \approx 9 \times 10^{26} \text{ m}$$

The corresponding energy scale is

$$H \approx 2 \times 10^{-33} \text{ eV}$$

This energy scale is closely related to the so-called “Hubble constant” that measures how fast the universe is expanding, albeit written in the unusual units of electronvolts. Clearly, it’s a tiny energy scale. A particle with the mass of H would have the same size as the entire universe.

This, then, is the playground of physics. The goal of physics is to understand everything that can happen at lengths in the range

$$10^{-34} \text{ m} < L < 10^{26} \text{ m}$$

or, equivalently, at energies in the range

$$10^{-33} \text{ eV} < E < 10^{27} \text{ eV}$$

It turns out that there is quite a lot of interesting things in this window! And, underlying many of them, is the Standard Model.

A Interlude: The Road to Discovery

Throughout these lectures, our focus will be on explaining the key ideas and concepts that underlie the subatomic world. This means that we will describe our current understanding viewed through the lens of the Standard Model. Yet this theory took many decades to build, years in which physicists were mostly bewildered and confused. It's important to ask: how did we arrive at this point?

The answer to this question is almost entirely: experiment. While there were many groundbreaking theoretical observations, at each step the important progress was only made in response to a novel experimental discovery. After each section of these lectures, we will have a short interlude in which we describe this experimental progress. This will also provide an opportunity to present a more historical approach to the subject of particle physics. The hope is that these interludes will serve to ground some of the ideas that we meet in the main thread, and place them in more concrete context.

In this first interlude, we explain the beginnings of particle physics. We describe the discoveries that resulted in the comforting and familiar picture of matter as made of just three particles: the electron, proton and neutron.

A.1 Ray Physics

Before particle physics was the study of fields, it was the study of rays. By the end of the 1800s, several kinds of “rays” had been found, each seemingly exhibiting different properties. It took several decades to distill the properties of these rays (do they undergo diffraction? can they be bent by electric or magnetic fields?) and, ultimately, to understand their particle constituents.

Cathode Rays

Take a glass tube, and remove most of the air. If you drop a large voltage across the tube, a faint glow can be seen at one end, a result of rays emitted by the cathode (the negatively charged electrode) hitting the glass wall. In many ways the discovery of these cathode rays, first observed in 1869 by the German physicists Hittorf and Plücker, marks the beginning of modern day particle physics.

A number of properties of cathode rays were soon established, including the fact that they travel in straight lines, as revealed by the shadow cast by objects placed in their path, but their trajectory can be deflected by both electric and magnetic fields. We now know that cathode rays are beams of accelerated electrons.

With hindsight, these early discharge tubes can be viewed as the world's first particle accelerators. The electrons were accelerated to energies of around 10^5 eV. In contrast, in the last electron-positron accelerator at CERN, known as LEP, electrons were accelerated to energies of around 2×10^{11} eV. Its successor, the LHC, accelerates protons to energies of 6×10^{12} eV. Evidently, the increase of energy by 7 orders of magnitude took 150 years of hard work. There are reasons to believe that the next 7 orders of magnitude will be even more challenging.

X-Rays

One recurring theme of particle physics is how one discovery paves the way for the next. The first example occurred in November 1895, when Wilhelm Röntgen was playing with cathode rays. He covered the glass tube with thin black cardboard and noticed that, when the tube was turned on, a paper screen painted with a chemical called barium platinocyanide would give a faint green glow, even when placed up to a meter away from the apparatus. He concluded that the tube was emitting some invisible rays, which he dubbed *X-rays*.

Röntgen's subsequent investigations showed that X-rays were not the same as the cathode rays from which they originated since they travelled much further in air. He also realised that X-rays could be used to develop photographic plates, and his [first paper](#) includes the astonishing photograph of his wife's hand shown to the right. His wife's perfectly reasonable response: "I have seen my death".

Röntgen's paper resulted in enormous excitement, both among other scientists and the general public. Rather like Einstein in later years, everyone wanted a piece of Röntgen. However, it appears that he was less than impressed with the whole show and worked hard to stay out of the lime-light. A sole newspaper interview from this time reveals a Dirac-like level of brevity:

Interviewer: What did you think?

Röntgen: I did not think; I investigated.

Interviewer: What is it?

Röntgen: I don't know.

The nature of X-rays remained mysterious for a long time. The suggestion that they may be short wavelength electromagnetic waves was not generally accepted since no one



succeeded in observing X-ray diffraction. This changed in 1912, when Max Laue (later von Laue) realised that the crystal lattice of solids had the right separation needed to observe diffraction of X-rays, opening up the entire field of X-ray crystallography.

Uranic Rays

Among the many people to be inspired by Röntgen's discovery was a French physicist named Henri Becquerel. For some years, he had held a fascination with phosphorescent materials and decided to explore the connection to X-rays. Ironically, in the end his discovery had nothing to do with X-rays.

Uranium salts had long been known to have phosphorescent properties. Becquerel's experiment involved exposing uranium to sunlight for several hours. With the uranium suitably excited, he observed that it emitted rays which, rather like X-rays, created silhouetted images on photographic plates wrapped in thick, black paper.

Becquerel's breakthrough came because of the weather. The final days of February 1896 were dark and overcast in Paris. With no sunlight available, Becquerel stored his experiment in the drawer of his desk and got on with other things, like a spot of shopping. By March 1st the sky remained cloudy and, perhaps bored, perhaps inspired, Becquerel decided to develop the photographic plate anyway, expecting to find nothing. Instead, to his astonishment, [there appeared](#) the clear image of a copper cross that had been placed between the plate and the uranium source. Becquerel's photograph is shown to the right.



Becquerel's desk drawer discovery showed that all his careful preparation, exposing uranium to sunlight, had nothing to do with the uranic rays that it emitted. This was, to say the least, disconcerting. If the rays were emitted without any prompting from an external energy source like the Sun then where did their energy come from? It was tempting to think that the whole thing violated the conservation of energy.

α , β and γ Rays

Soon after Becquerel's breakthrough, three further radioactive elements – thorium, polonium and radium – were discovered by Marie Curie (née Skłodowska) and her husband Pierre. The next step was to try to characterise the rays that were emitted. This was done by one of the early heroes of particle physics: Ernest Rutherford.

Rutherford was the first to realise that uranium emitted not one, but two different types of radiation. He called these α -rays and β -rays:

- α -rays: Alpha radiation is easily absorbed. Indeed, we now know that all α -rays would have been absorbed by the black paper wrapping the photographic plate in Becquerel's original experiment and so were not detected. Over a period of 13 years, from 1895 to 1908, it slowly became clear that α particles are four times heavier than hydrogen, with charge $+2$. In other words, they are what we now know to be the nucleus of a helium atom.
- β -rays: Beta radiation is more penetrating. In time, it was identified with a stream of electrons. This will be described below.

Later, Villard discovered that radium emitted yet a different kind of radiation, one that he naturally called...

- γ -rays: Another, very penetrating form of radiation. This was later found to be highly energetic electromagnetic waves.

Around the turn of the century, the situation was rather confusing. There were cathode rays and x-rays and α and β and γ rays. not to mention a number of false discoveries that were purely illusory. Getting to the heart of these phenomena would, ultimately, require an understanding of electromagnetism and the strong and weak nuclear forces.

A.2 The Electron

Cathode rays were the first to be discovered and, subsequently, the first to be understood in terms of a constituent particle. This particle is, of course, the electron.

The claim that rays are composed of particles means that their properties can be understood using Newtonian mechanics in which the particles are endowed with a mass m and electric charge e . In 1885, Hendrik Lorentz wrote down the equation of motion for such a particle moving in the presence of an electric field \mathbf{E} and magnetic field \mathbf{B} . A particle with velocity \mathbf{v} will experience an acceleration \mathbf{a} given by

$$m\mathbf{a} = e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \tag{A.1}$$

The first goal was therefore to measure the deflection of the cathode rays due to electric and magnetic fields. This measurement was performed by J.J. Thomson in 1897. Two other physicists, Wiechert and Kaufmann made similar measurements using only magnetic fields around the same time. However, as you can see from the equation of motion, the deflection of the rays cannot tell us about m and e individually: it only tells us about the ratio e/m .

Fortuitously, the same ratio e/m had arisen in an entirely different context the year before. This came from the discovery that the atomic spectral lines can be split in the presence of a magnetic field, a phenomenon known as the *Zeeman effect*. Lorentz himself analysed this effect using the equation (A.1) and, happily, the value of e/m that was needed to explain the observed splitting was close to that later found in cathode rays.

But the ratio e/m for cathode rays came with a surprise: it was significantly larger than the value for other known ions. (Thomson's measurement of e/m gave a value that was 770 times larger than that of a hydrogen ion – the particle that would later be rebranded as a proton. We now know that the correct value of the ratio is around 1836.) But the question remained: is this because the electric charge e of the particle is very big, or because the mass m is very small. To resolve this issue, one had to find a way to measure either e or m individually.

The prevailing viewpoint at the time was the right one: that the mass of the particle was unusually small. Indeed, there was already some indication of how small it had to be, since the electric charge on a hydrogen ion had been estimated to reasonable accuracy. This in itself was no mean feat. It was fairly straightforward to measure the electric charge on, say, a mole of ions. The difficulty is in figuring out how many atoms are in a mole. Or, in other words, in figuring out Avogadro's number $N \approx 6 \times 10^{23}$. (See the final question on this [Statistical Mechanics Example Sheet](#) if you want to challenge yourself.) A number of ingenious ways to determine N were proposed, resulting in a ballpark figure for e , the minimum unit of electric charge carried by what we now call the proton. One of the best estimates (out by a factor of 20 or so) was proposed by the Irish physicist Stoney, who also coined the name *electron*, for this “atom of electricity”.

A more direct measurement of the electric charge was [first achieved](#) by J.J. Thomson, and this is the reason that he, rather than Wiechert or Kauffman, is primarily remembered as the discover of the electron. He didn't study cathode rays, but he turned instead to the *photoelectric effect*. This occurs when UV light is shone on a material, causing electrons to be emitted, but at much slower velocities than those in cathode rays. Thomson measured the ratio e/m of these emitted particles and found that it agreed with his earlier measurements of cathode rays. But this time he could go further, employing a preliminary version of a detector known as the *cloud chamber*. This chamber contains supersaturated vapour which condenses into little droplets, or clouds, as a ray passes through and ionises the atoms. In this way, the path of the emitted object can be tracked.

In 1899, with his new cloud chamber toy in hand, Thomson was able to determine the number of negatively charged ions that formed due to photoelectric emission simply by counting the droplets along the path. He was also able to determine the overall electric charge by counterbalancing the effect of gravity with an electric field. In this way, he measured the charge on each individual droplet, getting within 30% of the electric charge that we know today. This was the first time that the cloud chamber gave rise to a major breakthrough in physics. It would not be the last.

A more precise measurement, employing a similar technique but using oil droplets rather than a cloud chamber, was performed in 1909 by Millikan and Fletcher. They again balanced gravitational and electric forces, but were able to observe individual droplets, deducing that the charge was always quantised in units of 1.6×10^{-19} Coulombs. Their measurement was within less than 1% of the modern value. Famously, Millikan struck a [dubious bargain](#) with his student Fletcher and the [resulting paper](#) was published under Millikan's name alone. No doubt he felt bad as he collected his Nobel prize twelve years later.

A.3 The Proton

The discovery of the proton went hand in hand with the discovery of the nucleus itself. The key experiment is one of the most famous in physics. Working in Manchester in 1909, Hans Geiger and his undergraduate assistant Ernest Marsden were firing alpha particles at thin sheets of metal and measuring how they bounced off. One day Rutherford entered the room and, according to Marsden, suggested “see if you can get some effect of α -particles directly reflected”.

The [results](#) were startling and entirely unexpected. About 1 alpha particle in 8000 was reflected back in the direction from which it came. In later years, Rutherford recounted his surprise in a well known quote:

“It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.”

But what did it mean?

The prevailing theories for the structure of the atom could not account for these experiments. Of course, physicists knew that atoms contained electrons, and there was acceptance that there had to be a compensating positive charge, but theories of the structure of the atom – whether based on plum puddings, planetary systems, or vortices – were put forward with little evidence.

The Geiger-Marsden experiment held the key. That it was Rutherford himself who understood its consequences is, in some ways, rather surprising. Rutherford was not known to hold much love for theoretical physics. He is reported to have said of relativity, “Oh, that stuff. We never bother with that in our work.” and he was never a strong proponent of Bohr’s founding work on quantum theory. My favourite Rutherford quote, capturing both his attitude to theorists, and his personality, is

“How can a fellow sit down at a table and calculate something that would take me – me – six months to measure in a laboratory?”

Nonetheless, when needed, Rutherford showed himself to be no mean theorist. [In 1911](#), he postulated that each atom contains a heavy, almost point-like object at the centre, carrying positive charge Q . He computed that an α -particle, repelled by the electrostatic Coulomb force, would be deflected by an angle θ with probability

$$\sigma(\theta) = \frac{Q^2 q^2}{4m^2 v^2 \sin^4(\theta/2)} \quad (\text{A.2})$$

Here q , m and v are the charge, mass and velocity of the α -particle. This formula is now known as the Rutherford cross-section. You can find a derivation in the lecture notes on [Dynamics and Relativity](#). The formula agrees with the experimental data with impressive accuracy.

As with many great discoveries in science, there was no small amount of luck involved. On the experimental side, the alpha particles used in the experiment were fast enough to blast through the electrons of the atom without care, but slow enough to be deflected from the nucleus before they experienced the strong nuclear force. On the theoretical side, Rutherford deduced his formula using Newtonian classical mechanics. But the correct calculation of the cross-section requires quantum mechanics and in nearly all cases this differs from the classical result. The Coulomb force law turns out to be the exception – it is the one force where classical and quantum results for scattering agree! (You can learn more about this in the scattering theory section of the lectures on [Topics in Quantum Mechanics](#).)

With Rutherford’s explanation of the nucleus, there was still work to be done. At the time, all elements were labelled by their atomic weight A which, at least for light elements, was close to an integer. Listing all the elements in order then gives two numbers: A , their weight and Z , their place in the list. The first few elements are shown in [Table 1](#).

	H	He	Li	Be	B	C	N	O
Z	1	2	3	4	5	6	7	8
A	1	4	7	9	11	12	14	16

Table 1. The first few elements

But the question remained: what is the physical meaning of Z ? In particular, if you’re just given the list of known elements, how do you know you’ve got them all? For example, it might be tempting to think that A is really telling us the rightful place in the list, with two missing elements with $A = 2$ and 3 that are just waiting to be found.

The suggestion that Z should be equated with the positive electric charge of the nucleus did not have an auspicious start. It was first made by van den Broek, a Dutch real estate lawyer who was [pushing](#) some new and improved 3d version of Mendeleev’s periodic table. His accounting of the elements never took off, but his suggestion that Z measures the electric charge was rapidly accepted. Moreover, Rutherford’s scattering formula ([A.2](#)) gives a clear way to measure the charge Q of the nucleus. These, and other experiments, ultimately led to the complete periodic table that we know and love today².

From here it was a short step to the idea that the hydrogen nucleus – originally called the H-particle – was a building block of all nuclei. The issue was finally put to rest some years later when Rutherford demonstrated that H-particles were emitted by other nuclei – specifically nitrogen – when bombarded by α -particles. The name “proton” was coined by Rutherford at this time.

A.4 The Neutron

In 1911, the nucleus was discovered. By 1920, there was no doubt about the existence of the proton. But it took until 1932 for the other constituent of the nucleus, the neutron, to be found.

²A physicist called Henry Moseley deserves special credit here. When Mendeleev originally proposed his periodic table he found gaps, allowing him to successfully predict the existence of three new elements. Moseley, using X-ray techniques to determine the atomic number Z , successfully predicted seven more!

Moseley, like many physicists of that time, was drafted into the Great War. Geiger and Marsden, for example, found themselves both posted to the Western front, fighting on opposite sides. Both survived. Moseley was not so lucky and the man widely recognised as England’s most promising young physicist was killed in the battle of Gallipoli by a bullet in the head. He was 27 years old.

In the decade between the discoveries of the proton and neutron, physics changed beyond anyone's wildest imagination. Quantum mechanics was formulated and the basics of quantum field theory were laid down. These ideas provide the foundation for nearly everything that we discuss in these lectures – both experimental and theoretical. Yet the discovery of the neutron owed only little to these new developments. The neutron took so long to find simply because it's hard to see. For this reason, the neutron still carries an air of that pre-quantum world, less exotic than, say, anti-matter whose origin story is so closely tied to developments in quantum theory. Yet, astonishingly, there was less than a 100 days between the discovery of the two particles!

You might wonder why physicists didn't stay up at night, puzzled by the difference between the atomic number Z and the mass A of the nucleus. It's because they had a very convincing explanation. They thought that the nucleus must consist of A protons with $A - Z$ electrons to cancel the charge. Moreover, there was an *extremely* good reason to think that the nucleus contained electrons. This was beta decay. The electrons emitted in beta decay are far more energetic than the orbiting electrons in the atom, and this meant that they had to have their origin in the nucleus. But if electrons were being emitted from the nucleus, then obviously they must have been there all along. That's simply common sense. Of course, we now know that common sense isn't always the best guide when it comes to the sub-atomic world.

If you knew where to look, the advent of quantum mechanics did make it increasingly difficult to believe in electrons in the nucleus. Trapped inside a cell the size of a nucleus, the Heisenberg uncertainty relation means that the electron necessarily has energy greater than 40 MeV, significantly larger than nuclear binding energies and making it untenable that the electron could remain in place. Further trouble came with the discovery of spin. (We describe spin in more detail in Section 2.1.) If both the proton and electron have spin $1/2$ then, regardless of whether spins add or subtract, a nucleus with A protons and $A - Z$ electrons should have integer spin when Z is even and half-integer spin when Z is odd. But that's not what's seen. Nitrogen, for example, has $Z = 7$ but was long known to have integer spin. Opinions differed on what to make of this. So ingrained was the idea that the nucleus contains protons and electrons that Fermi and Rasetti even wrote [a paper](#) suggesting that the mismatch should cast doubt on the idea of spin.

Still, when the breakthrough came it owed essentially nothing to new-fangled quantum ideas and everything to experiment. The first hint that something new was afoot came in 1930 in Berlin. Walther Bothe and Herbert Becker took alpha rays from a polonium source and directed them on beryllium. They [found](#) that the beryllium gen-

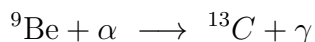
erated a new radiation of great penetrating power which they concluded, incorrectly, must be gamma rays. Over the next couple of years the experiment was repeated and improved, notably by Irène Curie who was sitting on the world's most powerful source of polonium, a gift from her mother. Together with her husband Frédéric Joliot (by that time both doubled-barrelled Curie-Joliot's), they directed this beam of supposed gamma rays at parafin and found that it could eject protons at huge velocities. But still they stuck with the gamma ray interpretation.

The Curie-Joliot experiment was the watershed moment. Their interpretation was not, it's fair to say, universally embraced. Apparently the Italian physicist Ettore Majorana responded to the news with the exclamation

“What fools! They have discovered the neutral proton, and they do not recognise it!”

In Cambridge, Rutherford and James Chadwick, his second-in-command, held similar sentiments. There was too much amiss for the radiation to be gamma rays. Less than three weeks later, Chadwick discovered the neutron.

In fairness, Chadwick had been searching for something like a neutron for over a decade. He didn't originally envisage a new elementary particle, but instead a closely knit bound state of a proton and electron, much smaller than a hydrogen atom so that it could fit inside the nucleus. That meant he was well prepared when the Curie-Joliot result came in. His [short paper](#) studies the penetrating power of the radiation. The Bothe-Becker-Curie-Joliot interpretation was that the original alpha rays react as



But the properties of the carbon nucleus were known well enough to put an upper bound on the energy of the emitted gamma ray. Whatever was coming out of this reaction was much more powerful. Chadwick found the correct conclusion: he was seeing something entirely new



Chadwick had found the neutron.