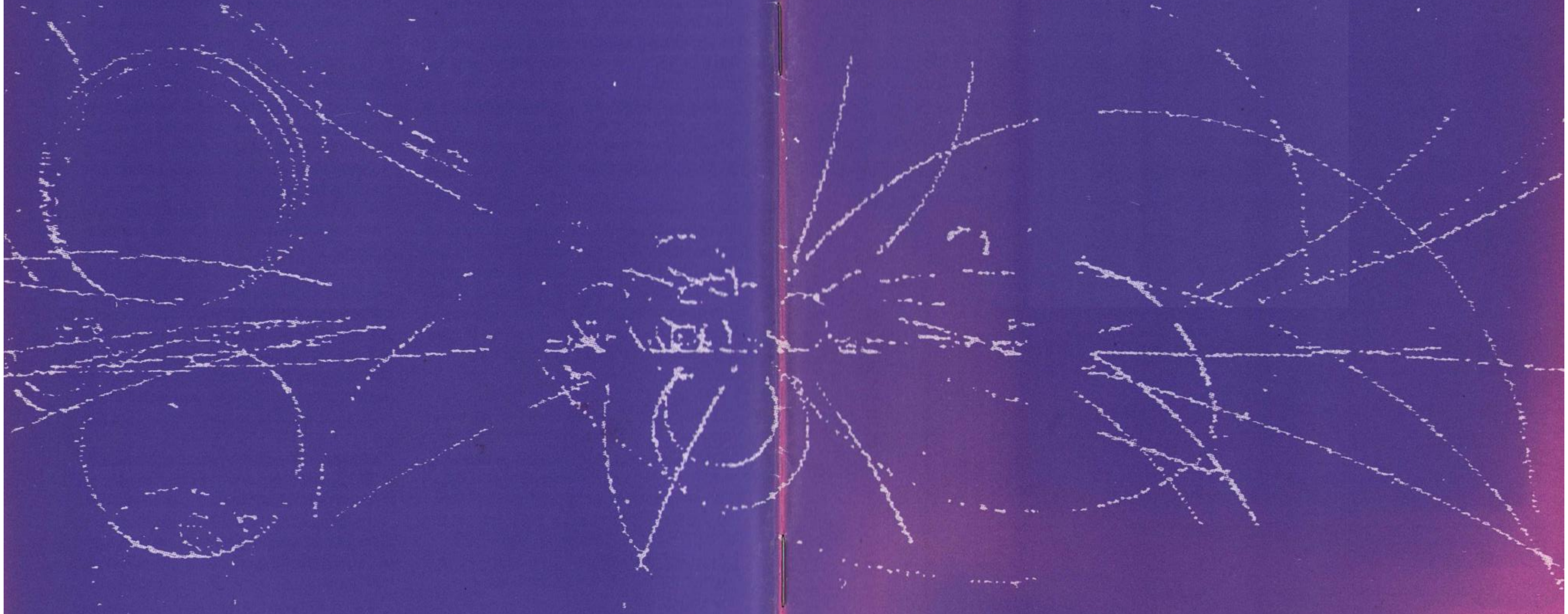
Atoms, Particles, Leptons and Quarks

A Rutherford
Appleton Laboratory
Monograph



serc

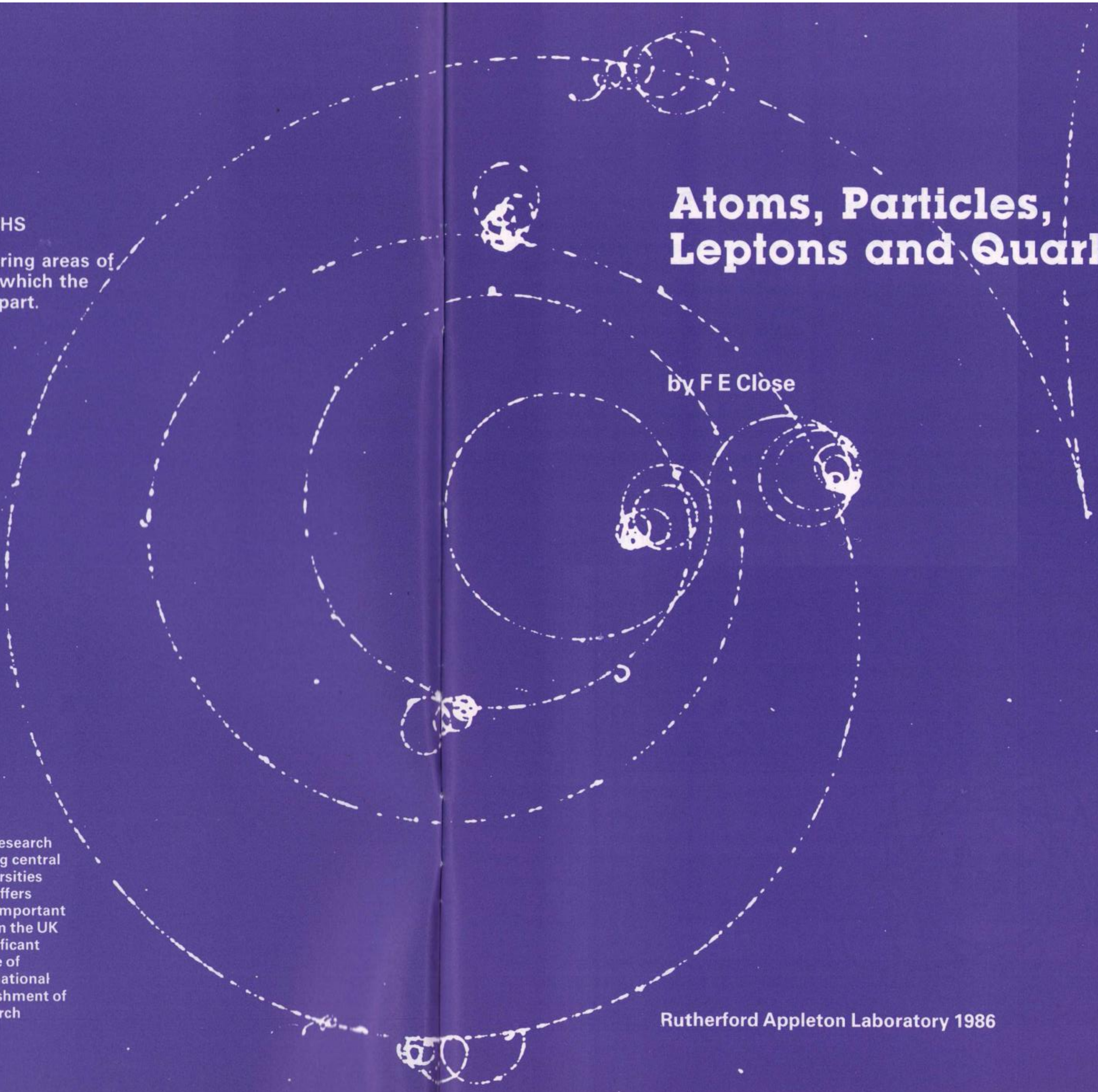
Science and Engineering Research Council,
Rutherford Appleton Laboratory,
Chilton, DIDCOT, Oxfordshire OX11 0QX.

Telephone Abingdon (0235) 21900

RUTHERFORD APPLETON
LABORATORY MONOGRAPHS

A series of short texts covering areas of science and engineering in which the Laboratory takes an active part.

Rutherford Appleton Laboratory supports and promotes academic research and development work by providing central facilities for use by individual universities and polytechnics. The Laboratory offers extensive resources and access to important facilities at other research centres in the UK and overseas. This results in a significant level of cooperation in a wide range of projects at both national and international levels. The Laboratory is an establishment of the Science and Engineering Research Council.



Atoms, Particles, Leptons and Quarks

by F E Close

Rutherford Appleton Laboratory 1986

Atoms, Particles, Leptons and Quarks

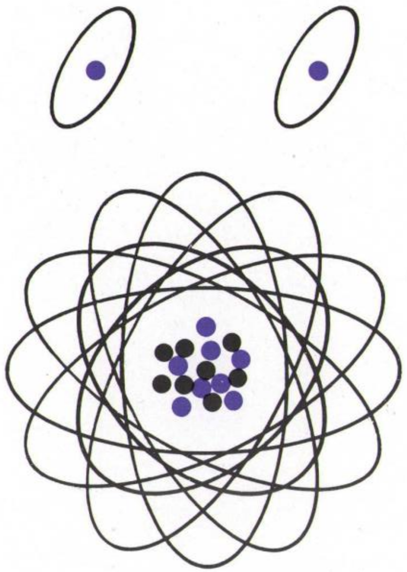


Fig 1 The water molecule, H_2O. The atoms are made of electrons (one for hydrogen and eight for oxygen) orbiting around a nucleus containing protons (and neutrons).

Introduction

Many years before the birth of Christ, the Greeks had proposed that matter is not divisible forever into smaller and smaller pieces. Instead, they conjectured, one will eventually find some ultimate pieces of matter which cannot be further divided and these they named *ατομοσ* (atoms). Even today we hold a similar belief, namely that deep down in the submicroscopic world are a *few* basic building blocks out of which all matter as we know it is constructed. Let us draw an analogy with language: a *word* is the smallest version of a sentence that can still be identified as a *sentence* (for example: 'Go!'); all of the words in the dictionary are made from just 26 *letters*. These 26 letters are the building blocks of language.

In the physical world, take some substance eg water (analogue of a *sentence* above). Now subdivide it. Eventually one will reach a molecule of water. This is the analogue of a *word*: it is the smallest bit of water one can have and still be identified as water. Subdivide it more and more and eventually one will find the basic building blocks. What are they, and how many types are there?

In the case of language the answers are known: they are the letters and there are 26 of them. In the real world the answers to these questions depend upon when you ask them. If you had asked an ancient Greek he would have answered '*ατομοσ*' However, today we know that what the Greeks called *ατομοσ* are really only molecules and that molecules are built of atoms (for example, Fig 1 shows a water molecule H_2O, which consists of two hydrogen H atoms and one oxygen O atom).

If you had asked the question at the beginning of this century you would have been told that the basic building blocks were the atoms. Today we know that there are over 100 different kinds of atoms, such as hydrogen, carbon, oxygen, uranium, etc, which can be conveniently arranged in a periodic table (see Table 1).

Table 1 The periodic table of the atoms.

CONVENTIONAL REPRESENTATION OF PERIODIC TABLE

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
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
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
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
87 Fr	88 Ra	89 Ac															

LANTHANIDES

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

ACTINIDES

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

With these atoms as the building blocks one can build up all of chemistry. However, several disturbing questions arise concerning these atoms. Why are there so many of them? Why is it that if we order them in increasing mass (as in Table 1) similar chemical properties periodically appear? Why does hydrogen (and for that matter the other atoms) have excited states which reveal themselves by the spectral lines emitted as the atom jumps from one state to another? How is it that atoms, which have no net electrical charge, manage to bind together electromagnetically and form molecules?

The answers to these questions become clear when one realises that atoms are not elementary but instead are collections of negatively charged *electrons* orbiting around a positively charged nucleus (the latter being built from positively charged *protons* and electrically neutral *neutrons*). One electron orbiting around a single proton forms hydrogen; six electrons around a nucleus containing six protons make carbon, and so on. The rules of quantum mechanics allow an electron in hydrogen to orbit only in certain well-defined configurations (described as S, P, D, F, . . . states). As the electron jumps from one orbit to another, the characteristic frequencies of light are emitted which form the spectrum of hydrogen (see Fig 2); similarly, characteristic spectra exist for all the other atoms. In an atom containing several electrons, the rules of quantum mechanics limit the number of electrons in any configuration. If one has an atom with N electrons (eg carbon has N = 6), then if one adds another electron, hence making an atom with N + 1 (in this case N = 7 is nitrogen), these rules tell you in which configuration the extra electron will prefer to go. This can then be shown to give rise naturally to the pattern shown in the periodic table. Finally the molecular binding emerges because the electrically neutral atoms have negative (electron) and positive (proton) charges contained within.

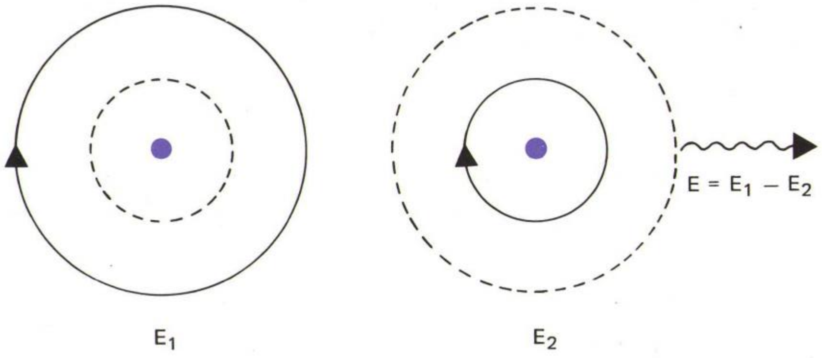


Fig 2 The spectrum of hydrogen: An electron jumps from a high energy orbit with energy E_1 to a low energy orbit E_2, emitting a photon of energy $E = E_1 - E_2$. This energy appears as a spectral line with wavelength $\lambda = hc/E$ (where h is Planck's quantum and c is the velocity of light). A complete spectrum results from electrons jumping between all possible orbits.

Since like charges repel each other, then electrons mutually repel and protons also mutually repel. Hence one would expect the atom to be a diffuse cloud of negative and positive electricity. The electrons in an atom do indeed repel each other and tend to occupy the outer reaches of the atom. Yet the protons have coalesced into a compact nucleus. The reason is that in addition to the electromagnetic force there is a force of attraction between the protons and neutrons which is strong enough to overcome the electromagnetic force which is trying to force the protons apart (see Fig 3). This strong force is not felt by the electrons.

Hence if one asked about the building blocks in the 1930s one would be offered the three elementary particles:

the electron (e^-), proton (p^+) and neutron (n^o)

Since 1930, in particular in the 1950s, many particles have been discovered. These particles are divided into the classes *'leptons'* (eg electrons) and *'hadrons'* (eg protons and neutrons) according to whether or not they feel the strong force.

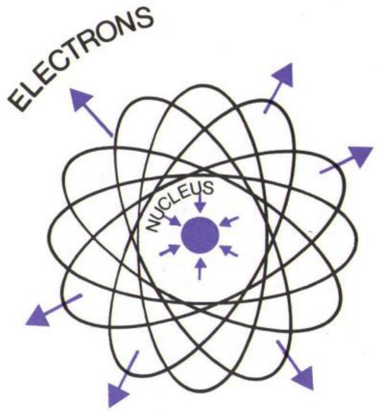


Fig 3 The forces in the atom. The strong nuclear force overcomes the electric repulsion.

Leptons —

particles which do not feel the strong force

By 1974, four leptons were known. First there is the familiar *electron.* The electron has almost no mass and can be thought of as a lump of negative electricity. Indeed it is possible that any mass that it has may be due to the energy associated with the electromagnetic field of its charge. If one removed the charge from an electron then you would remove its mass as well and be left with a massless, electrically neutral entity. Such a thing exists in Nature and is called the *neutrino.* It is denoted by ν_e, the subscript reminding us that it is a brother of the electron. The neutrino is produced as a product in the radioactive decay:

$$n^o \rightarrow p^+ e^- \nu_e \quad *$$

There is also a particle called a *muon* (μ^-). This appears to be identical to the electron in all respects except that it is much heavier. It too is accompanied by a neutrino, ν_μ, which is distinct from the electron neutrino. In weak radioactive decay processes the μ^- is accompanied by ν_μ, hence they are brothers analogous to e^- and ν_e above.

Even today it is believed that these four leptons are members of the true building blocks of Nature and that the weak interaction sees them as two separate pairs (e^-, ν_e) and (μ^-, ν_μ).

---

* The neutrino from this decay is in fact an *anti*neutrino – however, we will not introduce this complication here.

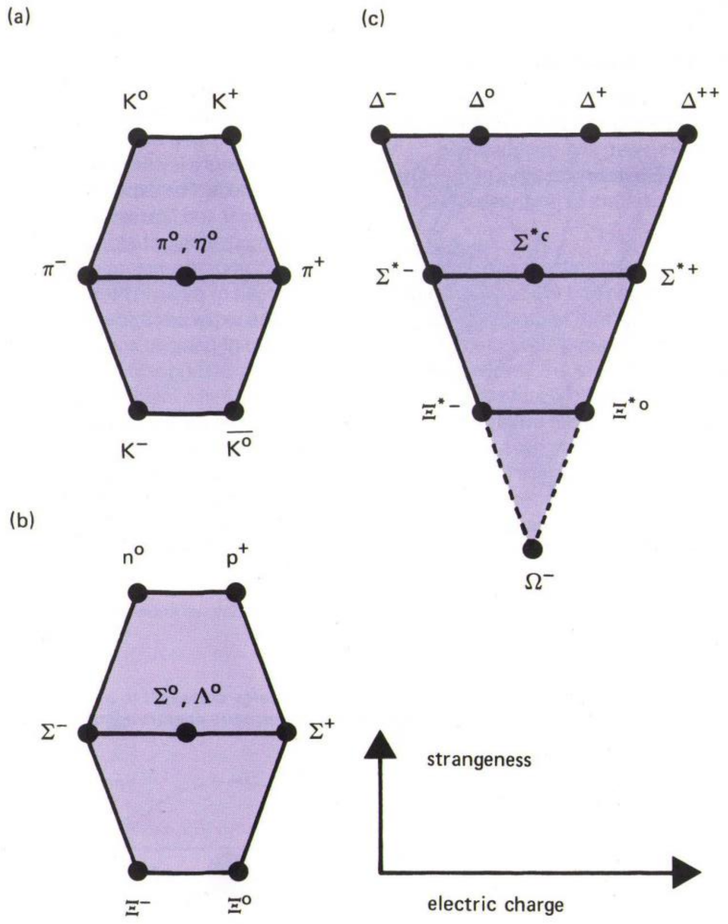
Hadrons —

particles which do feel the strong force

More and more hadrons were discovered through the 1950s and are continuing to be discovered today. This already suggests on aesthetic grounds that they are too numerous to be truly elementary. Several similarities with the atomic case suggest that these are not truly elementary building blocks. Indeed, their properties seem to suggest that they are but manifestations of a deeper layer of matter called *quarks.*

First of all there was the discovery that these particles formed patterns analogous to the periodic table for the atoms. Two examples of such patterns are shown in Fig 4. Particles called *mesons* fall into a hexagonal pattern on a two dimensional plot whose axes are electrical charge and a quantity called 'strangeness'. In addition, eight particles called *baryons* (including the neutron and proton) form a similar pattern. This is surely more than coincidence, and it led Gell-Mann to coin the phrase 'the eightfold way' to describe these patterns. He had an idea why these patterns might be emerging and as a test of the idea proposed that a pattern of ten should also occur. Nine of these were already known (Fig 4c) and so Gell-Mann bravely proposed that a tenth should exist. The pattern told him that it should have a negative electric charge. Since it was the 'last' link in the scheme, he called it the omega (Ω^-). The subsequent discovery of this particle in 1964 confirmed the eightfold way as a 'periodic table' of the particles.

Fig 4 The eightfold way patterns consisting of (a) eight mesons, (b) eight baryons and (c) ten baryons. The Ω^- baryon in (c) was predicted by Gell-Mann, and was subsequently discovered.



Quarks —

the building blocks of the hadrons

It was then realised in 1964 that these patterns emerged naturally if entities called quarks exist, and the observed particles are clusters of quarks (rather like nuclei being clusters of protons and neutrons).

Just as in the atomic case the excited states of hydrogen and the spectral lines emerge naturally from hydrogen's electron-proton internal structure, so in the particle case there are several particles that appear to be excited states of the proton or neutron. These emerge naturally if the proton and neutron have a multiquark internal structure (see Fig 5). The quarks can only sit in certain well-defined configurations (ie S, P, D, F, etc, states – like the electrons in hydrogen) and the excited states of the proton arise due to the possibility that one, or more, of the quarks is occupying a configuration of high energy rather than the ground state (lowest energy) configuration.

There is a final place where a parallel with the atomic example can be made. Rutherford inferred that the positive charge of the atom is concentrated in a localised nucleus. His experiments and those of Geiger and Marsden showed (Fig 6a) that positively charged massive α-particles* undergo violent collisions with atoms instead of passing straight through (as would be expected if the atom was a diffuse cloud of positive and negative electricity). This suggested that there was something rock-like inside the atom which was responsible for the violent collisions and was of positive electrical charge: the nucleus. In the late 1960s very high energy beams of electrons were fired at protons in a modern version of the Rutherford experiment (Fig 6b). History was

---

* Of course, today we know that α-particles are helium nuclei.

Fig 5 Spectrum of baryons: A quark jumps from a high energy state (p*) to a low energy state (p) emitting a photon (γ). This is analogous to the hydrogen spectrum in Fig. 2.

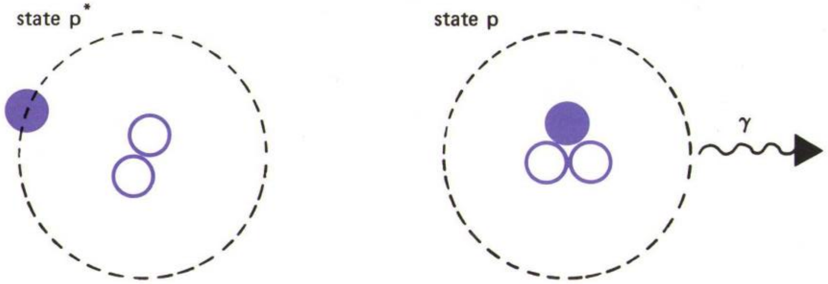


Fig 6 Sketch (a) illustrates Rutherford's early experiments in which α-particles were deflected by the complex nucleus in the atom. In recent experiments, shown in (b), high energy electrons are deflected by the localised charges (quarks) in the proton.

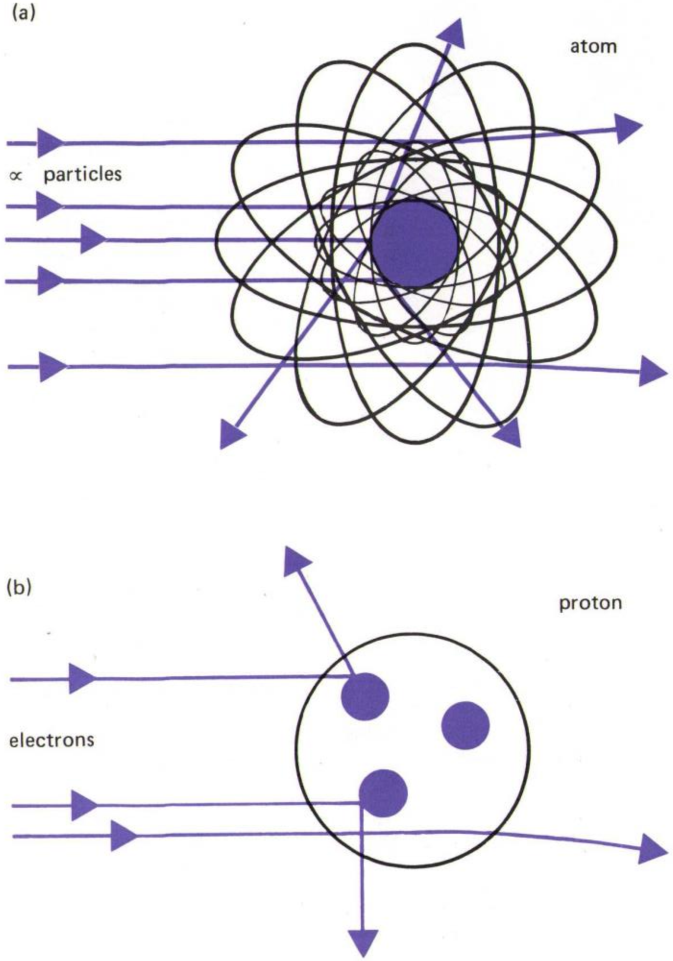
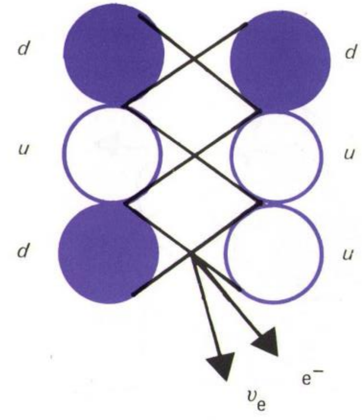


Fig 7 The radioactive decay $n^0 \rightarrow p^+ e^- \nu_e$ arising from the quark's radioactive decay $d \rightarrow u e^- \nu_e$.



repeated: the beam sometimes underwent violent collisions which suggested that the electrical charge of the proton is not spread diffusely through the proton but is instead localised on a few discrete centres of charge. These are the quarks mentioned above.

By 1974 three varieties or 'flavours' of quark were known. Two of these were called 'up' (*u*) and 'down' (*d*). They are intimate siblings in a way analogous to the e^- and ν_e being brothers. The quark radioactive decay (Fig 7):

$$d \rightarrow u\, e^- \nu_e$$

is the fundamental process which triggers the radioactive decay of the neutron (*ddu*) turning it into a proton (*udu*).

The electrical charges of *u* and *d* quarks are 2/3 and −1/3 of a proton charge, respectively. People have performed refined versions of the Millikan experiment to measure the smallest value of charge but have still not found any evidence for matter carrying an amount of charge less than that of the proton. It looks as if Nature forbids these quarks to exist as individuals and allows only clusters of 3, 6, 9, etc, or of quarks accompanied by an equal number of antiquarks ($q\bar{q}$, $2q2\bar{q}$, etc). The former are called baryons (like the proton), the latter are called mesons (like the pion which Yukawa postulated provided the strong force that holds the nucleus together). No one has yet produced a completely satisfactory explanation of the phenomenon that only $q\bar{q}$, qqq, etc, exist in Nature.

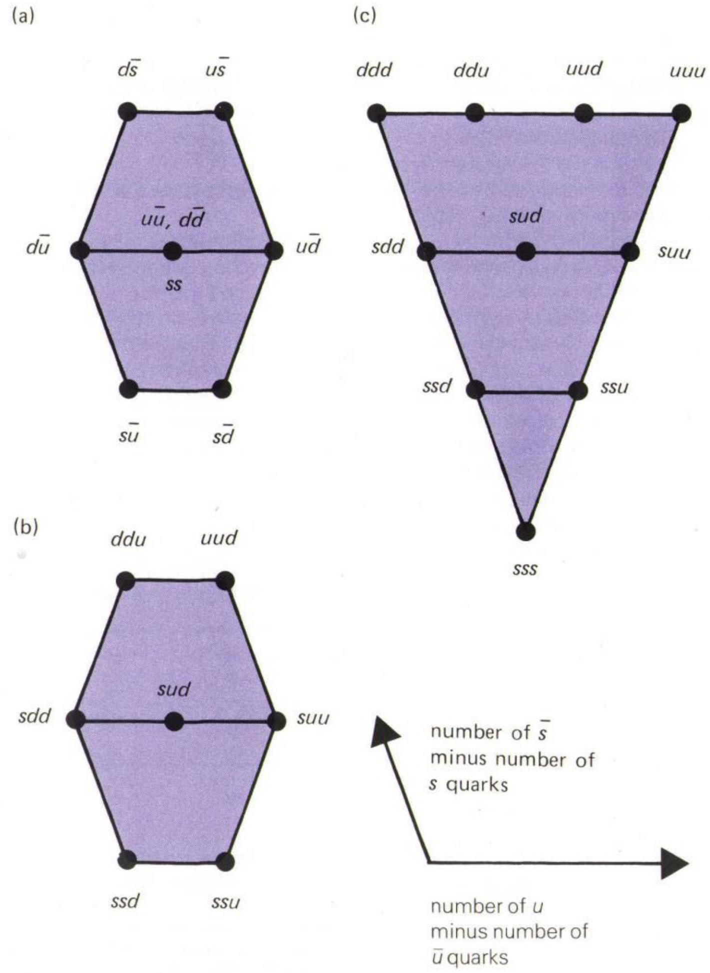
In addition to *u* and *d* there is a third flavour of quark. There are among the hadrons some particles known as *strange* particles (eg K, Σ, Ω^-). These are particles which contain one or more 'strange' (s) quarks. The strange quark has a charge of −1/3. With these three flavours, (*u, d, s*), the eightfold way pattern emerges in the particle spectrum (as shown in Fig 8).

A fourth quark: charm

In the leptons we find two pairs: (e^-, ν_e) and (μ^-, ν_μ). Among the quarks the (*d, u*) form a pair, so one might wonder if there is a fourth 'charmed' quark that will complete a pair with the strange quark: (*s, c*). The charmed quark will have charge 2/3 (like the *u*). Not only is this idea pretty, but it has profound consequences.

In the last century, electricity and magnetism were thought to be two quite

Fig 8 The eightfold way patterns emerging due to quarks for (a) the eight mesons, (b) the eight baryons and (c) the ten baryons, previously shown in Fig 4. Pattern (b) is like (c), but with the restriction that not all quarks can have the same label.



different phenomena. Then Maxwell united them in the modern theory of electromagnetism. Electric and magnetic forces were just two different manifestations of the same thing.

In the 1930s through until 1970, electromagnetism and the weak force of radioactivity were thought to be rather different. However, it has been shown that they may be two different manifestations of a single phenomenon called *flavour dynamics*, which contains electrodynamics and the weak force within it. This theory is extremely beautiful. It requires that the carriers of the weak force are W and Z bosons, analogues of the photons which carry the electromagnetic force. These W and Z bosons were predicted to be some 80 to 100 times heavier than the proton! Their discovery at CERN, Geneva, in 1983 proved that the theory is correct and led to the award of Nobel Prizes.

A crucial feature of the theory is that the fourth, charmed, quark must exist as a brother of the strange quark. There was tremendous excitement in November 1974 when two independent teams in the USA discovered a new particle, called J or ψ, which is a bound state of a charmed quark and a charmed antiquark ($c\bar{c}$). So significant was this discovery that the leaders of the teams won the Nobel Prize for physics in 1976. Several particles which contain a charmed quark have subsequently been found. By studying their properties it has been seen that the charmed quark is indeed a brother of the strange quark, apparently just as the unified theory of the weak force and electromagnetism required.

So if in 1975 you asked the question 'what are the building blocks and how many?', you would be told '*four* quarks and *four* leptons'.

A fifth lepton and a fifth quark

In 1975 there was the totally unexpected discovery of a new lepton called tau (τ^-). It was suspected that this may be partnered with a neutrino ν_τ. In 1977 came the discovery of a massive particle called the upsilon (Υ), some ten times heavier than the proton. It appears probable that it is a bound state of a new quark (named 'bottom', *b*) with charge –1/3.

Table 2 The new periodic table.

Leptons:	e^-	μ^-	τ^-
	ν_e	ν_μ	ν_τ
Quarks:	u	c	*
	d	s	b

The patterns evident in the Table lead people to conjecture that a sixth quark exists (although not yet found), labelled *t* for 'top', which will accompany the *b* quark at the position marked *.

Thus we have *five* leptons and *five* quarks (see Table 2). There is good evidence that the τ^- is indeed accompanied by a ν_τ, making *six* leptons. Our prejudices that leptons and quarks come in pairs have led many to conjecture that there is a *sixth* quark (*t* for 'top'), yet to be found, with a charge of 2/3 which is partnered with the *b* quark. In 1985 there was excitement when a possible sighting was reported. However this has not been confirmed and the hunt for top is still on.

So for over twenty years the answer to the question 'what are the building blocks' has been stable: 'leptons and quarks'. But the *number* of them has started to increase dramatically in the last few years due to the opening up of very high energy accelerators that are able to probe Nature at much shorter distances than ever before.

Do they indeed come in pairs? If so, why? Why are there so many? How many are there? The leptons and quarks are very similar in many of their properties – are they related in some profound way? Why do the quarks feel the strong force but the leptons do not? Most importantly, why does Nature allow us to see leptons but apparently keeps quarks confined inside the hadrons?

Theorists suspect that quarks and leptons are somehow related, and that we have not reached the end of the road in our search for the building blocks. However, a new feature has entered the picture. Previously we have been able to open up the atom and get the nucleus, open up the nucleus and get the proton. This time it is different. We cannot, it seems, open up the proton and get a quark. Whatever lies beyond the quark seems likely to be far more profound than anything that has gone before. It is believed by some that the answer may dramatically tie together not just weak radioactivity and electromagnetism but also naturally bring in the strong force that holds the nucleus together. Some clues in this direction have already been found and suggest that such a unification may be possible – but at the sort of energies where *black holes* may be formed! This suggests that in the ultimate synthesis the force of gravity too will play a role.

Recent discoveries have revolutionised our picture of the submicroscopic cog-wheels of Nature. Questions that were science fiction are now being seriously considered. The answers, and new questions, seem likely to be revolutionary.

More about particle physics can be found in 'The Cosmic Onion' by Frank Close (Heinemann Educational Books) and in 'The Particle Explosion' (Oxford University Press) by Close, Marten and Sutton. Both of these books are written at a level similar to this text.