

Quarks

Truth is Stranger than Beauty — or was that Up is more Charming than Sideways? A guide to the strange world of Atomic Physics by Robin Moorshead.

IT WAS THE GREEK PHILOSOPHERS who coined the term 'atom' as the basic indestructible building brick of all matter. They even realized that matter and energy were closely related when they said all matter was made of the elements fire, water, earth and air. However it was 2000 years before man really began to investigate the subject scientifically.

Modern science began with the parallel developments of physics and chemistry in the seventeenth and eighteenth century. These scientists discovered the true nature of chemical reaction which led to the idea that all matter consisted of a limited number of elements, which they believed were made of indestructible atoms. They thought that all that was necessary was to find out how many elements there were and that part of science was complete. At the same time Newton formulated the "universal law of gravitation" which was the first "force field" to be understood.

By the end of the nineteenth century the picture had become more complex. With the discovery of more elements it was found that they could be laid out in patterns and groups, a fact which strongly suggested that they had internal structure.

When the electron was discovered this single picture of the atom was finally shattered. But a new simple picture was developed consisting of electrons floating in positive charge clouds like currants in a bun. The physicists had added a second force field, the electromagnetic, to the list which helped them to explain the relationships between the positive and negative charges in the atom.

FORCES AND AGENTS

The discovery of radioactivity gave the physicists a new technique. As the unstable nuclei exploded the high velocity debris could be used to shatter other atoms. This soon led to the discovery of the proton, the neutron and two new forces.

There had to be an incredibly powerful force binding the protons together in the nucleus since the electromagnetic force should blow the tightly packed positive charges apart instantly. Secondly it was discovered that the neutron itself was radioactive, it would only live for about 11 minutes outside the nucleus. This suggested that there was another rather weak force which held together the parts of a neutron. They were named the strong nuclear and weak nuclear forces respectively. The disintegration of the neutron caused tremendous problems, since they calculated that apparently energy was lost when the event happened. The only way to explain this without abandoning the law of conservation of energy was to propose a fourth

particle the neutrino. This would carry away the missing energy. So when the neutron disintegrated this happened:

neutron \rightarrow proton + electron + neutrino

It was over twenty years before the neutrino was finally discovered.

The nineteenth century concept of a force field had by now given way to the idea that a force was transmitted by an "agent". So when two particles interacted they did so by exchanging the agent of the force. The agent of gravity was called the graviton (which has not yet definitely been detected). The agent of the electromagnetic force was the photon (which is easily detected). This meant that the strong nuclear force needed an agent which was called the 'mesotron'. But there was an important difference between the latter and the first two, since the gravitational and electromagnetic forces act over infinite distance, but the strong nuclear force acts over only 10^{-13} cm. The agents of infinite forces have no mass, but the mesotron had considerable mass. A new particle was discovered with the right mass but it didn't behave as predicted, a problem not solved until after World War II.

PARTICLES AND LAWS

Also at this time a particle called a 'positron' was discovered, it was opposite in every respect to the electron, in fact antimatter. Furthermore when it collided with an electron they annihilated one another producing a very energetic photon. This was confirmation of Einstein's equation $E=mc^2$ which mathematically relates matter and energy.

So to sum up the situation before World War II we have:

known particles:

- Electron
- Proton
- Neutron
- Mesotron (with some "wrong" qualities)
- Photon

Suggested:

- Neutrino
- Graviton

Forces:

- Gravitation
- Electromagnetic
- Weak nuclear
- Strong nuclear

Combined with this they had established several laws which governed particles' behaviour when they collided:

(a) Mass-energy is conserved ie: If two particles collide and create two new particles their combined masses may be greater or less than before but this is compensated for by them having more or less kinetic energy.

(a) Electric charge is conserved, ie: an electron cannot collide with a neutron and produce a positive particle, it must produce a negative one (and any number of neutral ones).

(3) Most of these particles spin, which again cannot be lost when they collide — like electric charge it must reappear in the new particles.

(4) At the time they believed also that any particle created through the strong nuclear force must disintegrate by it (likewise the weak nuclear). This was later found to be wrong.

The situation was quite satisfactory at the time, with a manageable number of particles and laws which governed all they had observed. But this simple picture was not to last long. Between the wars techniques had been developed to accelerate particles to immense velocity, so that they no longer needed to rely on radioactive disintegrations but could produce large numbers of very energetic missiles at will. Also they could see these events happening in "cloud chambers" where the particles would leave vapour trails exactly as high flying aircraft do.

It was with these techniques that the conundrum of the misbehaving mesotron was solved soon after World War II. In fact the mesotron they sought was found and it behaved exactly as expected, but it rapidly decayed yielding the particle they found before the war. So it had to be named and became the π meson (the first discovered) and the τ meson (the new particle). These are now known as muons and pions.

STRANGELY STRANGE

Now the trouble really started, most peculiar disintegrations were observed producing new particles which had no place in the scheme of things, and worse than that they broke the law that said if they were created by a strong interaction they must decay by it. They were created strongly and decayed weakly. Another feature of their creation was always being produced in pairs. An example of such a happening is shown in Fig 3, here a pion strikes a proton producing two new particles, a 'kaon' and a 'lambda hyperon', these then subsequently disintegrate to yield various known particles. This strange behaviour could be explained by analogy to the law of conservation of electric charge. If matter possessed a new quality like charge which had to be conserved when such a particle was produced so an opposite must also be produced. This quality was termed 'strangeness'. The kaon has a strangeness of + 1 and the lambda hyperon that of -1, the net result being zero change in total strangeness. Strangeness is now more commonly known as 'Hypercharge'.

The difficulties did not stop there, particles popped up all over the place and everything was in disarray, clearly it was necessary to classify the particles as the elements had been just 100 years ago.

The hadrons ("hard ones") are so named because they respond to the strong nuclear force. They themselves are divided into two subgroups on the basis of the way they spin, into baryons and mesons. Another

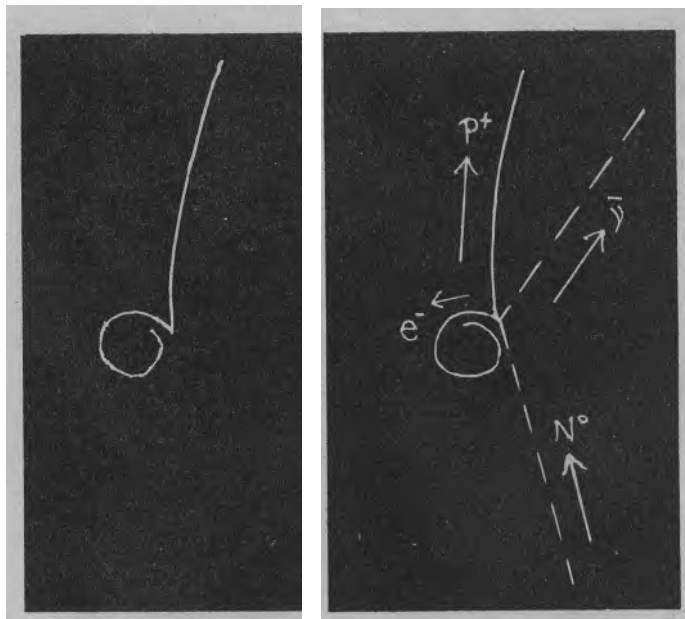
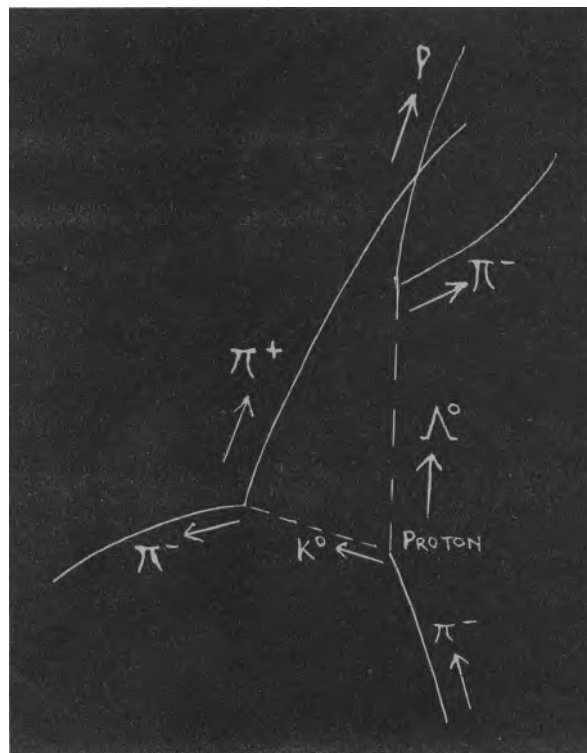


Fig 1 (top left) is what the disintegrations of a neutron would look like, meaningless at first but very meaningful on interpretation. The neutron enters from the bottom leaving no trail as it is ncharged, when it disintegrates it yields a light negatively charged electron which has a curved track due to an applied magnetic field, the proton curves in the opposite direction being positively charged but much less than the electron since it has 2 000 times the mass of the electron. So in fact to the physicist it becomes Fig 2- (top right). The hatched lines represent uncharged particles which do not leave trails.

Fig 3. (below) shows the formation of a kaon and lamda hyperon from a pion striking a proton.



difference is that mesons can be created in any number during a reaction, but the number of baryons is constant like total strangeness, ie if a baryon is created so must an antibaryon, and only a baryon can annihilate an antibaryon. The leptons are the 'small charge', little particles only involved in weak interactions. The photon is in a class of its own at present but would be with the graviton if it was discovered.

		Particles	Antiparticles	Name
Hadrons	Baryons	Ξ^0, Ξ^+	Ξ^-, Ξ^0	Ξ
		$\Sigma^-, \Sigma^0, \Sigma^+$	$\Sigma^+, \Sigma^0, \Sigma^-$	Sigma
		Λ^0	Λ^0	Lambda
	Mesons	n^0, p^+	\bar{n}^-, \bar{p}^-	Nucleon (proton, neutron)
K^0, K^+		\bar{K}^0, \bar{K}^-	Kaon	
π^+, π^0, π^-		π^-, π^0, π^+	Pion	
Leptons	μ^-, ν_μ	$\mu^+, \bar{\nu}_\mu$	Muon	
	e^-, ν_e	$e^+, \bar{\nu}_e$	Electron	
Massless boson		γ	Photon	

Fig. 4. Classification of particles.

As more and more particles appeared (over 100) they were all classified, and subgroups began to appear within the larger groups. The parallel to the classification of the elements 100 years ago is quite remarkable. Of course this immediately once again suggests internal structure.

UP, DOWN AND SIDEWAYS

In 1963 two independent workers came up with a system which would explain all the hadrons in terms of just three particles, the up, down and sideways (or strange) quarks, and their antiparticles. The leptons did not lend themselves to this explanation and are still regarded as truly elementary.

The baryons are said to be composed of three quarks and two mesons, one quark and one antiquark. (No satisfactory explanation of why there are no groups of one four, five or six quarks has yet been offered). The properties of the quarks are such that their sum would be that of the particle they make up.

		SPIN	ELECTRIC CHARGE	BARYON NO.	STRANGENESS
QUARKS	U (UP)	$1/2$	$+2/3$	$1/3$	0
	D (DOWN)	$1/2$	$-1/3$	$1/3$	0
	S (STRANGE)	$1/2$	$-1/3$	$1/3$	-1
		SPIN	ELECTRIC CHARGE	BARYON NO.	STRANGENESS
ANTI-QUARKS	\bar{U} (ANTI-UP)	$1/2$	$-2/3$	$-1/3$	0
	\bar{D} (ANTI-DOWN)	$1/2$	$+1/3$	$-1/3$	0
	\bar{S} (ANTI-STRANGE)	$1/2$	$+1/3$	$-1/3$	+1

Fig. 5

A proton for example consists of one down (d) and two up (u) quarks. So if the properties of the three quarks are summed up we have;

	U	U	D	OBSERVED QUALITIES OF PROTON
SPIN	$1/2$	$1/2$	$1/2 = 1 1/2$	(FRACTIONAL)
CHARGE	$+2/3$	$+2/3$	$-1/3 = +1$	
BARYON NO.	$+1/3$	$+1/3$	$+1/3 = +1$	
STRANGENESS	0	0	0 = 0	

Fig. 6

The important feature of spin is whether it is fractional or integral, the spin of the baryons is always fractional and that of the mesons integral.

An example of a meson could be the positive pion (π^+) which consists of one quark and one antiquark, the up (u) and the antidown (\bar{d}):

	u	\bar{d}	OBSERVED QUALITIES OF PION
SPIN	$1/2$	$1/2 = 1$	(INTEGRAL)
ELECTRIC CHARGE	$+2/3$	$+2/3 = +1$	
BARYON NO.	$+1/3$	$-1/3 = 0$	
STRANGENESS	0	0 = 0	

Fig. 7

The real justification for the quark theory can be seen by examining one of the "subgroups" found in the baryons. If one compares strangeness, electric charge and number of types per grouping ("isotopic spin") we get a group thus:

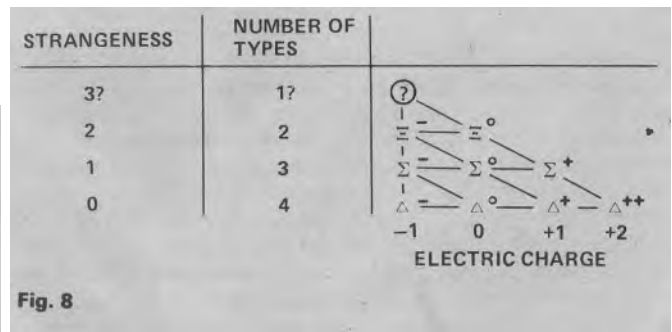


Fig. 8

This suggests another particle which would sit at the apex of the triangle. It would be a baryon, it would have no partners, and it would have three doses of strangeness. In fact it would be a baryon with three strange quarks (S,S,S). And sure enough it was found soon afterwards and is known as the omega minus (Ω^-).