ATOMS

An accurate historical account of the development of ATOMIC PHYSICS is probably the most hopeless task in the History of Science discipline. The story began, almost certainly, before the dawn of recorded history. Written records from Western antiquity date from as early as 450 BC, when the Greek Leucippus proposed that all matter was composed of $\alpha\tau o\mu$s, *i.e.* miniscule indestructible subunits of which there are only a few basic species. This view was picked up by Leucippus' student, Democritos of Abdera, some 50 years later and popularized by Epicurus of Samos around 300 BC, who developed the "Atomist" philosophical system that was epitomized by the Roman philosopher and poet Titus Lucretius Carus in about 60 BC.

Meanwhile, in 335 BC Aristotle countered with the proposition that matter was not grainy (as would seem to be required by the Atomist view) but smoothly *continuous* and composed of four basic ELEMENTS, also continuous: EARTH, AIR, FIRE and WATER. This picture gained popularity around 300 BC under Zeno of Cition, founder of the Stoics.

Thus the battle lines between a "bricks and mortar" view of matter and a "continuous" image of space, time and substance had been drawn well before the birth of Jesus; it took until the Twentieth Century to find the synthesis that allowed these two pictures (both of which, incidentally, are correct) to coexist in peace, though perhaps at the expense of what once passed for common sense.

Probably one key paradigm was Newton's CALCULUS, which taught everyone to understand CONTINUOUS mathematical behaviour in terms of DISCRETE "differentials" whose intervals were allowed to go to zero. Thus by the Ninteenth Century all scientists and mathematicians were intimately familiar with this trick for making the *smooth* look *grainy* and *vice versa*. The psychological stage was set for a new *physical* paradigm that reconciled Democritus' Atomism with Aristotle's Elements.

There was also an enormous amount of work done in the Middle Ages on determining exactly which ordinary household materials were true ELEMENTS and which were *combinations* of several elements — what we now call CHEMICAL COMPOUNDS. This was the work of untold numbers of ALCHEMISTS, most of whose work was done in secret for fear of persecution by those who considered such matters to be none of Humanity's business. Nevertheless, by the turn of the Nineteenth Century, a great many true ELEMENTS had been correctly identified and some regularities had begun to appear.

The next difficulty with the History of Atomic Physics is that a lot of it is Chemistry. Even after Alchemy became respectable under the new name of CHEMISTRY, a certain mutual disdain was cherished between Physicists and Chemists — which unfortunately lives on to this day — and consequently the History of Atomism reads a little differently in the Chemistry textbooks from the Physics version. Both are equally legitimate, of course, but since History is subject to politics and revisionism, one must always read any account with a certain healthy skepticism.

I will therefore make no claim that my account is fair, or even historically accurate; rather, my goal will be to show how the ideas *might* have developed in a perfectly logical sequence, using the powerful optics of hindsight. If you are stimulated by this "fake history" to go learn for yourself what *really* happened, then I will consider my goal achieved.

23.1 Modern Atomism

Most Physicists (and all Chemists) will probably agree that the crucial empirical observations that set modern science on the track of atoms (as we now know them) occurred around the transition between the Eighteenth and Nineteenth Centuries when a number of scientists including Antoine Laurent Lavoisier, Bryan and William Higgins, Joseph Louis Proust, John Dalton and Joseph Louis Gay-Lussac[1] discovered that certain chemical agents combined in simple integer ratios of their "MOLECULAR WEIGHTS" with other agents, a phenomenon most easily explained by assuming that these agents were the true chemical *elements* sought by the Alchemists[2] and furthermore that one MOLECULAR WEIGHT of *any* ELEMENT contained *the same number of* ATOMS of that element! This specific hypothesis is credited to Lorenzo Romano Amadeo Avogardo who in 1811 made a clear distinction between ATOMS (irreducible chemical units) and MOLECULES, which are clumps of atoms. For his trouble he got AVOGADRO'S NUMBER N_0 named after him. The actual *number* of atoms (or, for that matter, molecules) in one MOLECULAR WEIGHT (or MOLE) of the corresponding element is

$$N_0 \equiv 6.02205 \times 10^{23} \text{molecules per mole.} \qquad (1)$$

You may recognize this number from the Chapter on THERMAL PHYSICS, in particular the Section on the

[1] As you might guess, the details of the history of these discoveries also tend to vary with the nationality of the Historian!

[2] The Alchemists were already pretty certain of many of these, of course; but they were accustomed to keeping their mouths shut.

Kinetic Theory of Gases, the qualitative assumptions of which dated back as far as Robert Boyle, Robert Hooke and Isaac Newton himself in the late Seventeenth Century. The work of Daniel Bernoulli in 1738 foreshadowed the use of kinetic theory by Joseph Loschmidt in 1865 to make the first determination of the *value* of N_0 from measurements of the actual behaviour of gases. Statistical Mechanics actually played a major rôle in the development of modern Atomic theory, but its rôle is often downplayed in historical accounts simply because its is harder to understand. I will probably do likewise — but at least I admit it!

23.2 What are Atoms Made of?

By the end of the Nineteenth Century [I am leaving out a lot here!] most scientists were convinced that *atoms* were "real" (as opposed to a mere calculational aid or a handy mnemonic paradigm) and were looking for ways to determine their true structure.

23.2.1 Thomson's Electron and e/m

It was found that negatively charged particles called "cathode rays" could be coaxed out of a hot metal filament by a large enough electric potential and accelerated to hit a screen covered with phosphorescent material where they made a bright spot [the forerunner of today's *c*athod *r*ay *t*ubes or CRT's], but until 1897 no one knew much about the properties of these particles. In that year Joseph John Thomson used magnetic deflection (the Lorentz force) to determine the charge-to-mass ratio $\frac{q}{m}$ of the cathode rays.[3] He found an astonishingly large negative ratio: $\frac{q}{m} = -1.76 \times 10^{11}$ coulombs/kg, indicating that the electron (as the "cathode ray" particle soon came to be known) must be a very light particle (mass m_e) with a very large electric charge ($q = -e$) where the "electronic charge" e was thought until recently to be the quantum of electric charge — *i.e.* the irreducible minimum nonzero *quantity* of electric charge, in integer multiples of which all larger charges must come.[4]

[3] Such a device (for measuring the charge-to-mass ratio of electrically charged particles) is known as a magnetic spectrometer. Thomson's version was pretty crude by today's standards, but this is still the most accurate method for measuring the $\frac{q}{m}$ ratio of particles (and hence, if we know their charge by some other means, their *mass*).

[4] This is really the original prototype example of a quantized property. Many others were to follow, as we shall see.

23.2.2 Milliken's Oil Drops and e

Of course, this result revealed nothing about either e or m_e, just their *ratio*. But the absolute magnitude of e was determined ten years later by Robert A. Millikan, who watched tiny droplets of mineral oil through a microscope: the spherical oil drops, created with an ordinary atomizer (no pun intended), *fell* through still air in the Earth's gravity at a terminal velocity determined by their weight and the frictional drag of the air, both of which can be calculated from their radius. Now, every once in a while one of the drops would pick up a stray electron and become charged. If the experiment was performed in a vertical electric field of adjustable strength, the charged droplets could be made to "hover" by applying just the right voltage to overcome the force of gravity. Then, knowing the electric field, Millikan was able to calculate the charge.[5] The result was $e = 1.6 \times 10^{-19}$ C, which meant that the *mass* of the electron must be *really* small, namely $m_e = 9.1 \times 10^{-31}$ kg.

23.2.3 "Plum Puddings" *vs.* Rutherford

The discovery of that the electron was such an incredibly *lightweight* particle with such a huge *charge* made it perfectly clear that an atom must be something like a "plum pudding" — a homogeneous, featureless matrix of positive charge (carrying most of the mass) with the electrons embedded in it like raisins. Otherwise the electrons were apt to be *moving*, and this was unthinkable! If they were in motion but stayed inside the atom, then they must be continually changing direction. That means they must be *accelerated*, and by that time everyone understood only too well that

accelerated charges radiate!

Specifically, an accelerated charge (especially one with such a *large* charge-to-mass ratio) must always radiate away energy in the form of electromagnetic waves — it is a sort of *antenna* — and so the normal quiescence of matter "proves" that the electrons must be *at rest* in their atoms; this can only be so if they are "stuck" in a "plum pudding" of positive charge.[6]

[5] Naturally, sometimes he got *two* or *three* electrons on a drop; but this was simple enough to take into account: sometimes he got a result of e, sometimes he got a result of $2e$, sometimes he got a result of $3e$, but he never got a result of $\frac{1}{2}e$, for instance, so it was clear which result was the true charge quantum.

[6] This is truly an unavoidable conclusion if we accept the theory of classical electrodynamics at face value; it was not just a misinterpretation. You may be sure that hordes of Physicists looked high and low for a way out of this and found none.

In about 1910 a new type of "radioactivity" was discovered: certain nuclei spontaneously emit "α rays" which were shown to have a $\frac{q}{m}$ ratio nearly 4000 times smaller than electrons and where therefore much heavier particles. Soon afterwards, Ernest Rutherford set out to demonstrate the correctness of the "plum pudding" model of atoms by SCATTERING these α particles off gold atoms comprising a thin gold foil.

The picture is analogous to firing cannon balls at great slabs of gelatin in which are embedded many small marbles. The cannon balls will lose a lot of energy going through the gelatin walls, but they certainly won't change their direction of motion much.

To Rutherford's astonishment, most of the α particles passed right through the target foil without being deflected *or* losing much energy — indicating that what seemed to be "solid" metal was actually composed mainly of sheer vacuum. Even more alarmingly, *some* of the α particles *bounced backward* off the gold atoms — indicating that the mass of the gold atom was almost all concentrated in a tiny hard kernel of positive charge some 10,000 to 100,000 times smaller than the size of the atoms themselves!

As Rutherford himself put it, "*It is like firing shells at a piece of paper handkerchief and having them bounce back at you.*"

Scattering Cross Sections

Inasmuch as we are going to discuss modern ELEMENTARY PARTICLE PHYSICS later on, it is appropriate to stop for a moment and contemplate Rutherford's classic experiment, for the art of interpreting the distributions of SCATTERING ANGLES when a beam of one type of particle in a well-defined initial state is slammed into a target composed of other types of particles is essentially the entire experimental *repertoire* of the modern Particle Physicist.

Consider: the goal of the experimenter is to learn more about the *structure* of particles that are, individually, too small to be detected with a microscope. [If the particle is much smaller in size than the *wavelength* λ of the light used in the microscope, the best it can do is scatter the light into spherical outgoing wavefronts (HUYGENS' PRINCIPLE), from which we can learn nothing about the shape of the particle itself. The approved terminology for this limitation is that the RESOLUTION of the microscope can never be finer than the *wavelength* of the light it uses.] So how *can* we learn anything about the shape of the object particle? By SCATTERING other particles off it!

Imagine that there is an object hidden from sight behind a thin piece of paper; you have a BB gun which you can use to bounce BBs off the object. You get to to see which way the BBs bounce, and if you have a more fancy apparatus you may get to measure their velocities (momenta) before and after their collisions with the object; moreover, if any bits fly off the object as a result of a BB collision, you get to measure their directions and momenta as well. This is essentially the situation of the Particle Physicist. We may have a variety of PARTICLE BEAMS ranging from electrons to heavy nuclei, with energies ranging from a few eV to many GeV (billions of eV) or even TeV (trillions of eV) per particle — corresponding to peashooters, BB guns, rifles, howitzers and rail guns — but the only way we can use them is to shoot "blind" at our target particles and study the SCATTERING DISTRIBUTION.

You should try to imagine for yourself some qualitative phenomena you might look for to test various hypotheses about the target object — starting with Rutherford's test for "plum puddings" *vs.* hard-kernel ATOMIC NUCLEI. I will not attempt to develop the arcane terminology of scattering theory here, but I will mention the basic paradigm: the thing one can measure and describe most easily about a particle is the *area* it presents to an incoming beam; we call this the SCATTERING CROSS SECTION and measure it in area units such as BARNS [one BARN $\equiv$ $(10^{-13}\text{ cm})^2$ or 10^{-30} m^2)] — about the size of an average nucleus.[7]

23.2.4 A Short, Bright Life for Atoms

A new picture of the atom thus emerged, in which all the positive charge and virtually all the mass was concentrated in a tiny NUCLEUS at the centre of the atom and the light, negatively charged ELECTRONS orbited about it at rather large distances, much like the Earth and other planets about the Sun. This is a compelling and pretty image, and there is no problem calculating the orbital velocities of the electrons in the attractive central force of the nucleus.

The problem is, the *accelerations* of said electrons are *enormous*, causing them to *radiate* away their energy as electromagnetic waves (light) and spiral down into the nucleus. The lifetime of such an atom must be less than

[7] This humourous name for the *size of a target* may have marked the start of a trend toward "cute" nomenclature in Particle Physics, which manifested itself later in *strangeness*, *quarks* and (most recently) *truth* and *beauty* as particle properties — the latter pair now being retracted in favour of *top* and *bottom*, which I regard as a failure of nerve and will on the part of Particle Physicists. But that is yet another story. . . .

about 1 ns (or 10^{-9} seconds), during which time the atom gives off a bright pulse of light. Then, nothing.

This doesn't quite fit the data. Atoms are apparently quite stable and we are still here to talk about it, so there must be something wrong with this picture. Naturally, armies of Physicists went to work trying to find fault with the logic of classical electrodynamics, but there was no way out; the predictions were too simple to be mistaken. Something was seriously wrong.