One discovery inside another

ARISTOTLE shared with Plato the view that different kinds of matter are composed of earth, air, fire and water in appropriate proportions. Understandably, the ancients concentrated on the qualities of matter. A brief chronology of succeeding events will clarify where we are now.

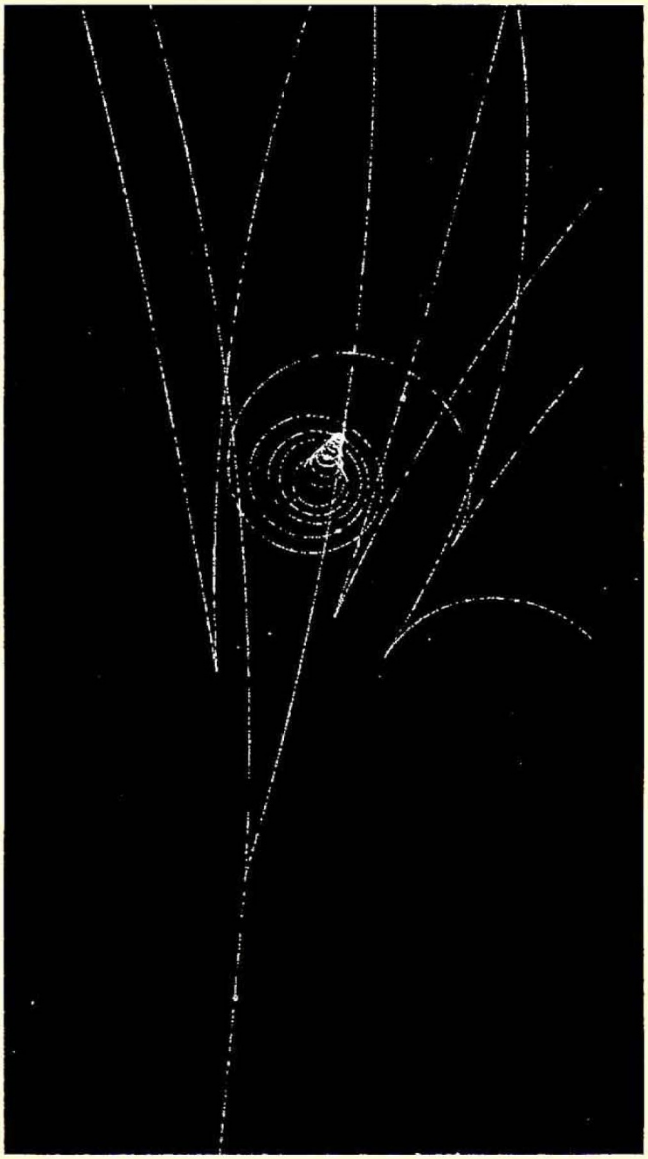
■ In the four decades between Lavoisier and Dalton, the atomic theory was established. The size of an atom (of the order of 10^{-10} m in diameter) and the periodic table arrived only in the last third of the nineteenth century.

■ J. J. Thomson announced the discovery of the electron in 1897, Rutherford established the nuclear atom in the succeeding decade and Bohr published his semi-classical model of the quantum atom in 1913. The transmutation of elements by natural radioactivity was a proof that nuclei are not immutable.

■ Dirac, having (in 1928) made a relativistic version of Schrödinger's equation for an electron in an electromagnetic field, famously predicted the existence of a positively charged electron; the discovery of the positron followed (Anderson, 1931). Each particle except the photon (which is its own antiparticle) has such a *Döppelganger*. The hunt for unstable particles in cosmic rays was thereby intensified, while Yukawa (1937) proposed that forces between nucleons are mediated by particles called mesons (then known to the cosmic-ray community as 'mesotrons') which, although massive, would otherwise function much as photons mediate electromagnetic forces.

■ W. Heisenberg, in 1932, proposed that neutrons and protons are but two almost degenerate states (in the quantum sense) of a single entity, called the nucleon. This step was conceptually important because (a) it introduced a new quantum number, called isotopic spin (otherwise isospin) into the description of nuclear matter which, after nearly 30 years, (b) led directly to the notion of the quark.

■ C. F. Powell and his colleagues[1] used the ionized tracks of cosmic rays in photographic plates to demonstrate, in 1947, that the candidate mesons in cosmic rays are of two kinds, the pion and the muon. (The former is the supposed mediator of the internucleon force; the latter turns out to be a heavier version of the electron.) In the same year, the particles called 'strange' were discovered[2] in cosmic rays, heralding the coming of the quark.



Lawrence Berkeley Laboratory — where bubble chambers were pioneered

A positive kaon (K^+) comes in from the bottom of this bubble-chamber picture, hitting a proton and producing a shower of subatomic particles. The kaon was the first of a whole family of 'strange' particles identified in cosmic rays. (Reproduced from *The Particle Explosion* by F. Close, M. Marten & C. Sutton, Oxford University Press, 1987.)

■ The commissioning of particle accelerators producing protons with energy of the order of 10^9 electron volts (eV) made possible the artificial production of antiprotons (with negative, not positive, electric charge). More significantly, in 1964 an experiment at the accelerator at the Brookhaven National Laboratory confirmed the reality of a particle called Ω^-, whose existence had been conjectured only.

■ Meanwhile, in the 1950s, theoreticians (Feynman, Schwinger and Tomonaga among others) were developing a quantum version of electrodynamics that satisfied the requirement that it should also be relativistic. Quantum electrodynamics (QED) was a conceptually crucial step. There are two interacting entities: an electron field and an electromagnetic field, represented by its four-dimensional potential. Quantization of the latter ensures that electromagnetic energy exists in the form of photons, with energy $h\nu$, where h is Planck's constant and ν the frequency. But both the electron field (represented by a wavefunction) and the electromagnetic potential contain elements of ambiguity; the former, for example, can be multiplied by a complex function of unit modulus without changing the physical interpretation that the squared modulus of the wavefunction represents electron density. The potential is similarly ambiguous. So the numerical values of the two interacting fields (or, more correctly, the phases) can be redefined at all points in space and time. That is the gauge principle, central to all later theories of particle fields.

■ The prediction of the existence of the Ω^- had been based on a classification of newly created unstable particles made independently by Gell-Mann and Ne'man. Part of their purpose was to account for the multiplicity of the particles already found; high-energy physics needed a periodic table, which in retrospect is a way of classifying the known atoms by means of quantum numbers of which Mendeleev was necessarily ignorant. (The first row of the table is filled by the elements H and He because the Pauli exclusion principle prevents more than two electrons from occupying the lowest electron state.)

That breakneck series of developments is the origin of particle physics as it had become by 1960 or thereabouts. □

1. Lattes, C.M.G., Occhialini, G.P.S. & Powell, C.F. *Nature* **166**, 453–456 (1947).
2. Rochester, G.D. & Butler, C.C. *Nature* **166**, 855–857 (1957).