13. J. J. GIBSON

The Mechanism of Perception

James Gibson was born in 1904, in McConnelsville, Ohio. His family were strict Presbyterians, and he was brought up in that faith. He did not retain it into adult life. His education was completed at Princeton University, where he took his PhD in 1928. For many years he worked at Smith College. At that time Smith was an institution exclusively for women. He married Eleanor Jack, in 1932. His wife was also a psychologist and much of his subsequent work was done in collaboration with her. Perhaps the famous cookie-cutters came from the Gibson kitchen.

After many years at Smith the Gibsons moved to Cornell University, where, apart from interruptions in the war and several extended visits abroad, James Gibson spent the rest of his life. During the Second World War he worked with the Air Force on the problem of effective training programmes for pilots. He is credited with the discovery that has revolutionized instruction in landing an aircraft, that whatever the angle of descent, the only point ahead which shows no parallax, that is does not change its relation to other things in the environment as the plane descends, is the point at which the aircraft will touch down. It has been said that this was the occasion of his discovery of the important role played by geometrical invariants in the process of human perception.

Gibson's work centred round one main problem: how does a photographed bridging the gap between one haploid bacterium and another. These photograps add a dimension to the actual experiment, which refers to the mechanism of direct genetic transfer only very indirectly and via a network of inferences, the validity of which depends upon our being ready to accept the general picture. Each step in the Jacob and Wollman reasoning is hypothetico-deductive. Suppose that a segment of DNA is being drawn in, what should we expect? It is the expectations that are being tested in the experiment and its subsidiary investigations. Only with the electron microscope photographs is the cycle of reasoning completed, by a more or less direct verification of the hypotheses behind the testable expectations.

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recipient they simply switched on the kitchen blender and beat up the mixture, so physically rupturing the fragile strands of DNA. By diluting the mixture they prevented any fresh contacts being made. They tested the resultant culture every few minutes to see which properties had been passed on from the Hfr to the F− cells. By 'plating' the cells, that is putting them on a nutrient jelly, which had been dosed to kill off the Hfr strain only, they were able to test for Hfr behaviour in the surviving F− cells.

As Jacob and Wollman put it, 'the extremity, O (for 'origin') enters first, to be followed by T+L+ [a specific combination of markers] eight to nine minutes later, and then by other markers in the order of their arrangement on the chromosome and at intervals of time proportional to the distance between them . . . until the whole segment had been transferred.' This took about 35 minutes. So the order of recovery of the characteristics associated with the markers gave a perfect map of the order of the physical layout of the marker genes on the DNA of the cells from which the fragment had come. By making use of the fact that on different occasions the markers are incorporated at different points in the DNA of the Hfr and F+ strains, leading to breaks at different points in the ring of DNA of the host cells, a great deal of the structure of the DNA chain can be explored directly.

By studying the usage of energy by different strains of bacterial cells Jacob and Wollman were able to find further indirect proof for the picture of genetic transfer I have sketched in this section. By starving the Hfr cells but feeding the F− strain, they were able to stop the process of transfer. This suggests that only the Hfr cells were using energy in the initiation of the transfer. But once contact had been made and times the point of weakness where the forking starts may break apart, with an active tip, an 'origin', as it has been called. The breaking of the ring in this way occurs only in Hfr and F+ cells. It seems to be due to a molecular constituent of the DNA itself, and so is heritable.

When a break occurs in a cell which is close by an F− cell, the active origin tends to break out of its original cell and enter the adjacent cell, pulling with it the remains of the DNA thread attached to it. The inserted fragments can enter the DNA of the F− cells, changing its genetic constitution directly. Jacob and Wollman took advantage of this phenomenon to find the order of genes on the fragment of donor DNA that was drawn into the recipient cell. Their basic piece of equipment was a kitchen blender. If the process of insertion could be stopped, and the strand which is being pulled in by the F− factor at the active tip of the thread be broken off, a small number of genes would be slowly drawn in. As each gene becomes attached to the DNA of the receiving cell it will change the capacity of that DNA to manufacture proteins and so alter the behaviour of the whole cell. This suggests that 'there should be a definite relationship between the times at which a given marker [that is a gene which has a definite and detectable effect on the behaviour of the recipient cell] is transferred from the Hfr to the F− cell and the location of the marker on the Hfr chromosome.'

The experimental technique was very simple. Jacob and Wollman mixed up a culture of the right combination of strains of bacteria. They knew from previous experiments that it took about 2 hours for the process of transfer of genetic material from Hfr to F− cells to be complete. To stop the process of transfer with only a short piece of donor DNA drawn into the

The experiment

To follow Jacob and Wollman's method for directly transferring genetic material from one cell to another some preliminary information is needed, and some technical terms must be introduced. With some exceptions plants and animals are reproduced cell by cell, through different kinds of process. Cells proliferate by simple division, 'mitosis'. Daughter cells have just the same genetic constitution as the mother cell from which they come. These are called 'vegetative' cells. The other process involves two cells as parents. Half the genetic material of each parental cell migrates to each end, and both cells split in two, to form 'gametes'. Each has half the genetic material needed for reproduction of a complete offspring. One gamete from each parental cell come together to form a pair, and fuse, with each contributing its half to the total complement of genetic material. This process is called 'meiosis'.

There are some cells which can divide only by mitosis. Cells which divide by meiosis must have a double complement of genetic material in their complete state. Cells with two sets of chromosomes are called 'diploid' cells. Those with only one set of chromosomes in the complete form are called 'haploid'. Clearly haploid cells can divide only by mitosis. Most bacteria are haploid, so they must reproduce by mitosis, and in consequence there would seem to be no way in which genetic mixing could take place, as it does naturally in division by meiosis.

If there is no meiosis it seems that it would be impossible for one strain of bacteria to pass on any of their heritable characteristics to another strain. Yet as long ago as the 1920s, it had been shown that dead virulent pneumonia bacteria could somehow pass on their virulence to live non-virulent strains. In 1952 Hayes found that a very small proportion of a common had been found for tracing a given bodily feature back to the place on the strand of genetic material (or DNA as it has come to be called) which was the ultimate source of that feature in the growing organism. All kinds of ingenious indirect methods of 'genetic mapping' had been worked out. The basic idea behind these methods depends on picking out sets of characteristics which are inherited together. In sexual reproduction half the genetic material from the mother cell is recombined with half the material from the father cell to form a complete new complement of genes. In such recombination all sorts of different associations can be formed. By studying the statistics of recombination in many generations it is possible to make pretty good guesses as to which pairs of characteristics are close together on the genetic material, since they will tend to be inherited together much more frequently than those which are further apart. By working patiently on hundreds of such pairs it is possible to build up a map of the genetic layout of a chromosome.

Two lines of further development suggest themselves. Could some more direct way be found of determining the order of genes and locating sets of them on the chromosomal material? If genes are physically located in this way could methods be developed for excising some genes and replacing them by others, simply by cutting out and putting back lengths of DNA? The experiment to be described in this section answered both these questions in the affirmative, at least in principle. Jacob and Wollman showed how to determine the order of a set of genes more or less directly, and, at the same time, they found that there was a mechanism by which genetic material was lost from and inserted directly into the DNA of single cells.

carry a latent tendency to pass on to its offspring characteristics which it does not itself develop. The simplest explanation of this phenomenon, and other features of the process of inheritance, is that there are genetic factors, physical 'things' which are present in living creatures, and which are responsible for inheritance. These physical 'things' came to be called 'genes'. Where were they located in the physical body of an organism?

Microscopical studies of the division of cells had shown that there were rod-like bodies in the nuclei of cells that split into pairs during reproduction. One member of each pair migrated to opposite ends of the cell. In this way a pair of nuclei were formed, and the cell divided so that one was in each daughter cell. The rod-like bodies could be made visible by staining the cell with a dye, and so came to be called 'chromosomes', the 'coloured bodies'. For various reasons it began to seem likely that the genetic units, or genes, which controlled heredity, were associated with or perhaps even were the component parts of chromosomes.

Three problems were posed by this theory and its associated images. What was the chemical constitution of the chromosomal material? What were the genetic units or genes, that is how was the structure of a chromosome related to its genetic potential as a carrier of the physical basis of inherited characteristics? How were the genetic units organized, for instance did they lie along the strand of material that had been identified as the chromosome? The first question required a chemical answer; the second a biological solution; and the third required an understanding of how the chemical components of the material of the chromosomes were related to the biological units or genes.

The solution to the first problem, the purely chemical question, came from the work of J. Watson and F. Crick company director. He was educated at the Lycée Carnot and then at the University of Paris. From 1950 he has worked at the Institut Pasteur in Paris, in a group of molecular biologists of the highest distinction, including Jacques Monod. He became Laboratory Director in 1956. Since 1960 he has been in charge of the whole programme of cellular genetics at the Institut. Though he has become very well known for his experimental researches, carried through with great ingenuity and economy of means, he has not confined his writing to the reporting of his laboratory work. Like many distinguished French intellectuals he has also commented on the general philosophy of his science. His work, *The Logic of Living Systems*, is a discussion of the general theory of biology. In 1965 he was appointed Professor at the Collège de France. In that year he was awarded the Nobel Prize, sharing it with Jacques Monod.

In 1947 he married Lysiane Block. According to an intriguing note in *Who's Who in France*, Professor Jacob admits to taking a greater interest in his hobby, painting, than in his official vocation, microbiology.

Élie Léo Wollman was born in 1917. He was educated in Paris, and has been one of the group at the Institut Pasteur. He became Vice-Director in 1966.

The biology of inheritance

Modern theory of the mechanism by which offspring inherit the characteristics of their parents begins with the discoveries of Gregor Mendel. He is best known for his formulation of the laws of inheritance and the idea that there are dominant and recessive characteristics. This idea suggests that an adult can

A

Finding the Hidden Mechanism of a Known Effect

The sciences can be thought of as two-dimensional structures. In the horizontal plane, so to speak, are represented well-established correlations between observed causes and their observable effects. But theoreticians and experimentalists pursue studies in a second dimension, to try to find the mechanisms which produce the observable correlations. The two cases to be described in this section illustrate two different ways of pursuing the quest for explanation. The experiment of **F. Jacob** and **E. Wollman** involved an ingenious isolation and manipulation of the hidden mechanisms of heredity, mechanisms which were later revealed to more or less direct observation by the use of electron microscopes. **J. J. Gibson** demonstrated that a whole new theoretical orientation was required to understand the known human powers of perception, an orientation which had many direct and indirect consequences. In each case the experiment enriched the content of a field beyond the phenomena immediately observable at the time.

had been formulated by Maxwell, were to be the same for all systems of bodies in any kind of relative motion. Then just as in the old physics there could not be mechanical tests for 'real' motion, so the new physics would imply that there could be no electromagnetic tests. In particular the Michelson–Morley experiment could never work. To complete the programme Newton's Laws would have to be changed so that they would be the same for all systems of bodies, no matter how they moved, according to the rules for electromagnetic laws. If Newton's Laws, invariant under the old Galilean transformation, could be altered to be invariant under a new mathematical condition, one that was tailor-made for Maxwell's electromagnetic laws, then a perfect unity could be achieved. This new harmony was achieved in the Special Theory of Relativity.

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relative to the ether the greater the force it will experience, causing it to contract along the line of motion. So, according to Lorentz, the Michelson–Morley experiment gives a null result because the arm of the apparatus that is laid along the direction of motion of the earth as it moves through the ether, has contracted just enough to compensate exactly for the time taken by the light pulse in that direction. As Lorentz himself put it, 'surprising as this hypothesis may appear at first sight, yet we shall have to admit that it is by no means far-fetched, as soon as we assume that molecular forces are also transmitted through the ether, like the electric and magnetic forces of which we are able at the present time to make this assertion definitely. If they are so transmitted, the translation will very probably affect the action between the two molecules or atoms in a manner resembling the attraction or repulsion between charged particles. Now since the form and dimensions of a solid body are ultimately conditioned by the intensity of molecular actions, there cannot fail to be a change of dimensions as well.'

An alternative explanation of the null result follows from Einstein's reformulation of the basic laws of physics. It should be remembered that his work was independent of the Michelson–Morley experiment. Einstein believed deeply in the ultimate unity of the physical world and the simplicity of its fundamental processes. Suppose that *all* the laws of nature were the same for all systems of bodies, including the laws of electromagnetism, the exceptions in the old physics. The old physics had taken Newton's Laws for granted. But suppose physics were to be thoroughly revamped, starting with the electromagnetic laws and presuming that these laws, as they rotated the whole apparatus very slowly and steadily in its bath of mercury. They were able to study the fringes while the stone slowly turned without being troubled by distortions. They performed two sets of observations each day, one set at noon, and the other at six in the evening. In this way they hoped to eliminate any effects due to daily changes in the weather. For the noon observation the stone was rotated anticlockwise, and in the opposite sense for the evening.

If we return to the diagram in which the basic structure of the experiment is laid out, we can see that the failure to detect a difference in the length of the paths of the light pulses in the two arms of the apparatus deals a fatal blow to the idea of using the ether as a stationary background against which to measure the 'real' motion of the earth.

But how was the result of the experiment to be explained? Perhaps there is a compensatory change. The apparatus is assumed to be rigid. But suppose that it contracted along the direction of motion, squeezed up by the ether, by just the right amount to compensate for distance the Detector 1 had moved? This would explain why Michelson and Morley failed to detect any change in the fringes. This was Lorentz's solution, and has been called the 'Fitzgerald–Lorentz' contraction after the two men who proposed it.

A more radical explanation involves abandoning the underlying picture of the physical structure of the universe assumed in the design of the experiment, in particular giving up the idea of the ether. If there were no ether there would be no foundation for expecting the result. We could accept the result at its face value. If light had the same velocity, not only with respect to the imaginary ether, but with respect to *whatever* real detector it was measured by, we would expect no positive result meant that the effect was small and so difficult to detect with certainty. Both difficulties were overcome in the final arrangement.

Instead of moving the apparatus to the second position, and then waiting for it to settle, Michelson and Morley found that they had much clearer optical effects and less distortion if they

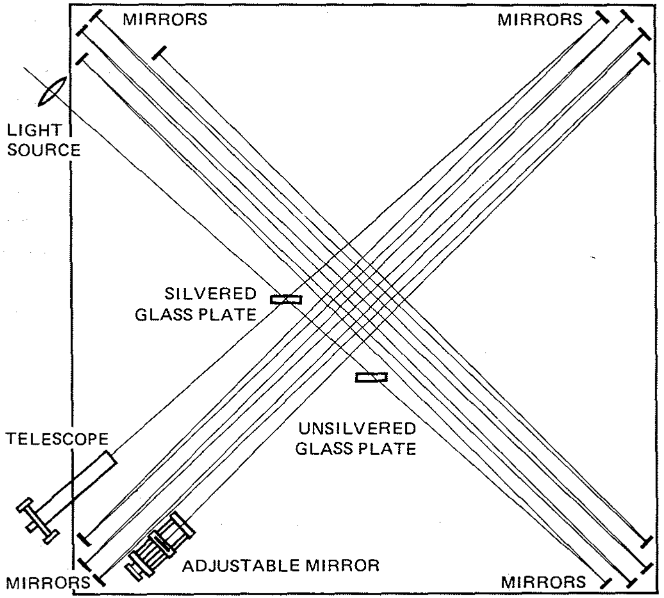


Fig.25. Plan diagram of the final apparatus, redrawn from the illustration in Michelson and Morley's 1887 paper in the *American Journal of Sciences,* 3rd series, vol.34.

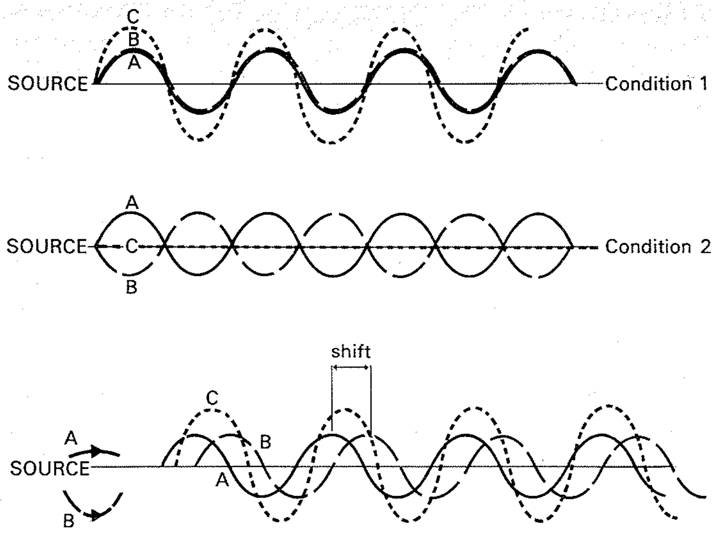


Fig.24. Shift in the interference fringes: explanatory diagram.

experiment of 1887, with Morley, took account of this effect.

The whole apparatus is assumed to be moving with the earth through the ether. Simple mathematical analysis shows that the difference between the observed lengths of the paths of light in the two perpendicular directions should be Dv^2/c^2, where D is the length of the arm of the apparatus, v is the velocity of the earth through the ether, and c is the velocity of light. As Michelson and Morley point out, 'only the orbital motion of the earth is considered. If this is combined with the motion of the solar system, concerning which but little is apparatus. But how could such a very minute difference be detected? The trick was to use the phenomenon of interference fringes. This phenomenon comes about because in one aspect of its behaviour light is like a wave motion. With the wave picture in mind we would expect to detect interference effects when two waves combine (see fig. 24). If the waves A and B combine as in Condition 1 troughs and crests coincide to give an amplified effect. But in Condition 2 troughs and crests will cancel each other out, giving darkness. Suppose A and B come from the same source, but reach the point where they start to recombine by different routes. If the paths of A and B differ by exactly one wavelength we would expect to get Condition 1, but if they differed by half a wavelength we would get Condition 2. Suppose however that we start with Condition 1 and then contrive to make the path of A just a very little shorter than that of B. The crests of B would now arrive before the crests of A. Then the highest point of the combination of the crests would be shifted slightly to the left. By this 'shift' an observer could tell whether the path A had changed in length.

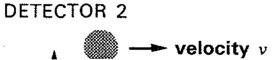
White light is a mixture of lights of different wave-lengths, and for each wave-length there is a different colour (though in practice the eye cannot discriminate to the extent that is theoretically possible). Because of the mixture of waves, when interference effects are studied with white light the bright peaks of full combination of waves are surrounded by coloured fringes. It was to the detection of shifts in these fringes that the Michelson–Morley experiment was directed. Pl.3

Michelson's first attempt to measure the motion of the earth through the ether took place in 1881. But he had overlooked 'the effect of the motion of the earth through the ether on the path of a ray of light at right angles to this motion'. The

If Newton's Laws are the same whatever the relative motions of the systems to which they are applied, there is no way they could be used to determine whether any system of bodies, say our own galaxy, is really at rest. But if light is due to the spread of vibrations in a stationary ether, then this ether might do as a fixed background against which to measure all motions.

The experiment

Imagine a light pulse sent out from a source in the direction of motion of the source. If the light pulse is transmitted by the stationary ether its velocity will be always the same, regardless of the motion of its source or of a detector. Its velocity is constant relative to the *ether*, not its sources and detectors. Now imagine a light pulse sent out at right angles to the direction of motion of a source, and with a detector the same distance from the source as the one for the first pulse. We now have a set-up as in the diagram below. If the source and detectors are imagined to be rigidly bolted to a frame and so are all moving through the *stationary* ether, and both light pulses are moving with the same definite velocity in that ether and relative to it, then the time taken by light pulse 1 to reach the detector 1 will be longer than that required for light pulse 2 to reach detector 2. Detector 1 will have moved on ahead while the pulse of light is moving through the ether at its fixed speed. *l*1, the length of the rigid bar holding the source and Detector 1 together, will seem to be longer than *l*2, the length of the bar



theories of light of Descartes and Newton, since both conceived of light as a stream of particles. Evidence that light has a definite velocity came originally from astronomical observations. Olaus Roemer noticed that the intervals between the eclipses of the moons of Jupiter were different when the planet and the Earth were approaching each other from when they were receding from each other. A simple explanation of this effect is that the light, having a definite and finite velocity, takes a shorter time to reach the Earth when the planets are approaching each other, and a longer time when they are receding. These observations were made in 1675.

Ideally the velocity of light ought to be measured in an earthly laboratory with all the precautions against disturbances that make for a reliable result. No really satisfactory method was available until 1849, when H. L. Fizeau devised an ingenious and simple method, easily set up in a laboratory. The results were consistent with the velocity calculated on the basis of Roemer's observations.

What was light? The particle theory of Descartes and Newton had slowly been replaced by a wave theory. Light was thought of as a transverse vibration in a universal medium, the ether. The ether was supposed to permeate the whole universe, and to be the stationary background to all motions. To grasp how this idea relates to Newton's conception of a mechanical universe we must notice a peculiarity of his famous Laws. They have an important mathematical property, called Galilean Invariance. This property means that Newton's Laws of Motion are the same for all bodies, no matter how fast they are moving relative to each other or to the imagined stationary ether. It follows that there is no mechanical way of detecting one's absolute motion.

such as the standardization of the metre against the wavelength of cadmium light.

Having divorced his first wife, he married Edna Stanton in 1899. He returned to the Navy during the First World War as a Reserve officer, and worked on the development of optical range finders. After the war he spent more and more time in California. This was partly for pleasure but he was also working on some new projects, including measuring the diameter of the stars. Once again the velocity of light absorbed his interest, and he began working with apparatus set up on adjacent mountain peaks, giving much longer distances between source and detector.

Michelson was much honoured in his life time. He received the Copley Medal of the Royal Society, and was the first American citizen to be awarded a Nobel Prize. He died in Pasadena in 1931.

Edward Williams Morley was the other member of the famous team. He could hardly have come from a more different background. He was born to strict Congregationalist parents in Newark, New Jersey, then a country town, in 1838. His father was a minister in the Church, and Edward was schooled at home by his parents. Not till he was nineteen did he have any public education, when he went to Williams, his father's college. He was intended for the ministry, and after taking his first degree began studies at the Andover Theological Seminary in 1861.

He began his teaching career at the South Berkshire Academy in 1866. It seems that he taught both theology and general science. In 1868 he married Isabella Birdsall, and in the same year became minister to the Congregational Church in Twinsburg, Ohio. Western Reserve College was nearby at

Albert Abraham Michelson was born at Strelno in Prussia in 1852. His father seems to have been something of an adventurer. When Michelson was still an infant the family migrated to the United States. Michelson's father set up in business trading with the gold miners of Nevada. The child was brought up in Virginia City, a classic 'gold rush' town. He was boarded away from home for his later schooling, in San Francisco. Proving exceptionally able he completed his higher education at the U.S. Naval Academy at Annapolis, though he had some troubles fulfilling the entry regulations. After a tour of seagoing duty in the Navy he returned to the Academy as an instructor in the physical sciences. In 1877 he married Margaret Heminway, and so acquired a very wealthy father-in-law.

His interest in the measurement of the velocity of light seems to have begun about 1878, and his first experiments were conducted in that year, with apparatus paid for by his father-in-law. From 1880 to 1882 he did postgraduate study at several European universities, notably with Helmholtz in Berlin. There he began to study the optical effects of interference between light waves, with equipment paid for by Alexander Graham Bell, the telephone engineer.

Having resigned from active naval duty in 1881, he returned to the United States in 1882 and joined the Case School of Applied Science in Cleveland. By then Morley had begun his work at the neighbouring Western University. The famous experiment was done in 1887.

In 1889 Michelson moved to Clark University, and then in 1893 to Chicago to head the physics department of the new university. By this time his interests had shifted from the problem of the velocity of light to other uses of interferometry,

F

Null Results

What if an experimental procedure is carried through and there is no result at all? One of the most famous of all experiments, that of **A. A. Michelson** and **E. W. Morley**, involved a manipulation that had no measurable effect. If this happens there are two possible explanations to hand. The manipulation did produce an effect but there was a reciprocal effect too, which 'cancelled' the first one out, so to speak. Sometimes experiments contrive to test a hypothesis by deliberately producing such a cancellation. But it might be that the theory in terms of which the result aimed at was to be expected is not just wrong, but somehow conceptually incoherent. In the case of the experiment to be described in this section both kinds of explanation were tried out. Eventually one of the latter sort came to be accepted as the most fruitful way to account for the null result.

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amount, and what is more, they were of very long range (19 cm). To what could they be due?

Rutherford began a long series of subsidiary experiments to answer this question. Each experiment was designed to eliminate a possible source for the mysterious fast particle. There are some swift oxygen and nitrogen atoms produced by collisions with α-particles, but these have a range of about 9 cm only. By using a screen between the chamber and the detector screen, which had a stopping power greater than 9 cm of air, 'these atoms are not completely stopped'. He showed that the anomalous effect was not due to water vapour since it still occurred with carefully dried air. It was not due to dust particles since carefully filtered air produced the same effect. But if it were due to the nitrogen of the air, in some way, then the long-range particles should continue to be produced and perhaps even increase, if nitrogen from some chemical source was introduced. And that is exactly what happened. The increase was precisely what would be expected as the amount of nitrogen is increased from 80 per cent as in atmospherical air, to 100 per cent.

'The results so obtained show that the long-range scintillations obtained from air must be ascribed to nitrogen.' But the next step was to show that they are due to collisions with α-particles. This could be presumed if there were any evidence that they were due 'to collisions of α-particles with atoms of nitrogen throughout the volume of the gas'. One obvious test would be to change the pressure of the gas. If the number of scintillations decreased directly proportional to the decrease in the pressure of the gas then this would be good evidence. Further, Rutherford showed that the range of the expelled atom that produced the scintillation was proportional to the right order, but the 'numbers involved were too small' for him to be satisfied with the experiment as a proof. But everything added up to the near certainty that that was what the long-range particles were. Now for the interpretation of the experiment.

'... we must conclude', says Rutherford (p. 586), 'that the nitrogen atom is disintegrated under the intense forces developed in close collision with a swift α-particle, and that the hydrogen atom which is liberated formed a constituent part of the nitrogen nucleus.' But this interpretation must not be just fudged up *ad hoc* to explain the effect – it must be able to be seen as a natural extension of theories already well established. Rutherford goes on to show how the new effect fits in. 'Considering the enormous intensity of the forces brought into play, it is not so much a matter of surprise that the nitrogen atom should suffer disintegration as that the α-particle itself escapes disruption into its constituents.' From nitrogen

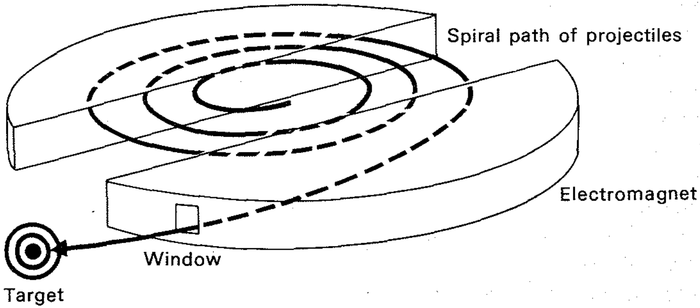


Fig.22. The path of a beam in an accelerator.

University of Manchester. He immediately attracted around him a group of very talented younger men. He was awarded the Nobel Prize for chemistry in 1908. In 1909, in collaboration with Geiger and Marsden, he carried out the experiments that suggested that atoms consisted of heavy nuclei surrounded by orbiting electrons. At first this discovery was not widely recognized, but it began a very fruitful period of collaboration between Neils Bohr and Rutherford, in the course of which Bohr sketched out the quantum theory of fundamental particles and their interactions.

During the First World War Rutherford worked on problems of submarine detection, but at the same time managed to continue his major researches. The discovery of the artificial disintegration of elements and their forced transmutation came in 1919, the experiment to be described in this section. In 1919 Rutherford finally returned to Cambridge, succeeding J. J. Thomson as Director of the Cavendish Laboratory. Here he worked with Chadwick on systematic studies of the artificial disintegration of the elements, and it was here that with Oliphant and Hunter he produced the first nuclear fusion, the creation of atoms of a heavier element by fusing the atoms of a lighter one.

He was awarded the Order of Merit in 1925 and elevated to the Peerage in 1931. He died in Cambridge in 1937.

The state of knowledge before Rutherford's experiment

In trying to set out the history of the problem of the transmutation of the elements a great deal depends on what one takes the term 'elements' to mean. In antiquity the distinction between compounds and elements, as we know it, which had either passed right through the gas in the chamber or had been emitted by collisions between α-particles and molecules of the enclosed gas.

When this apparatus is equipped with a Radium-C source to produce α-particles and filled with air, there appear 'scintillations on the screen far beyond the range of the α-particles' emitted at the source. At first sight they seemed to Rutherford similar to the 'swift H [hydrogen] atoms produced by passing α-particles through hydrogen'. When an α-particle hits a hydrogen atom it gives it a 'shove', projecting it with very high velocity and long range. When oxygen or carbon dioxide (i.e. constituents of air other than nitrogen) were introduced into the apparatus the scintillations due to long-range particles were much reduced. 'A surprising effect was noticed, however, when dried air was introduced.' Instead of the number of long-range scintillations being reduced it was increased by a large

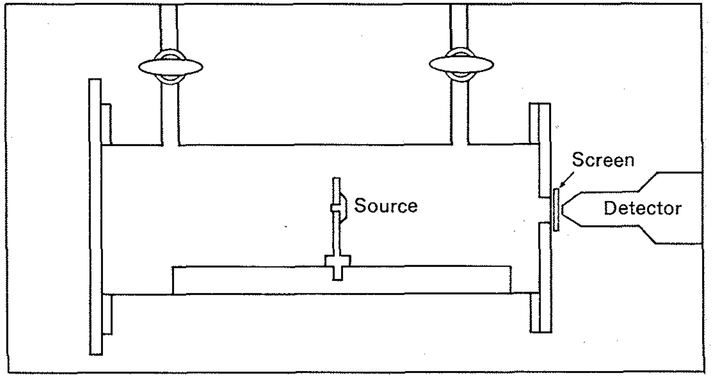
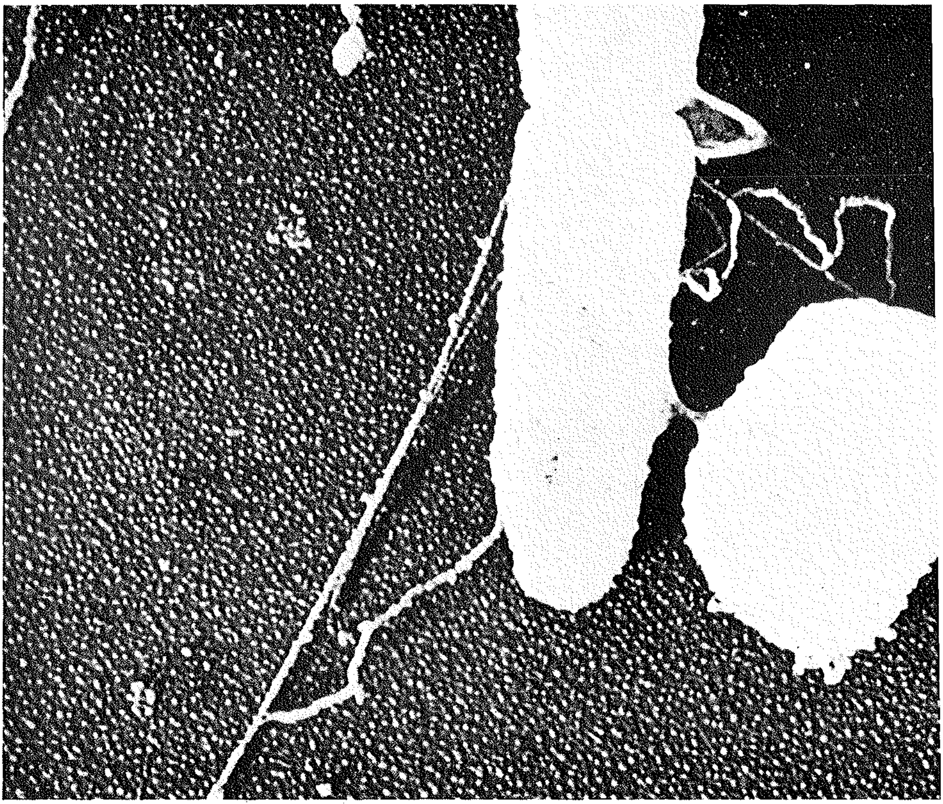


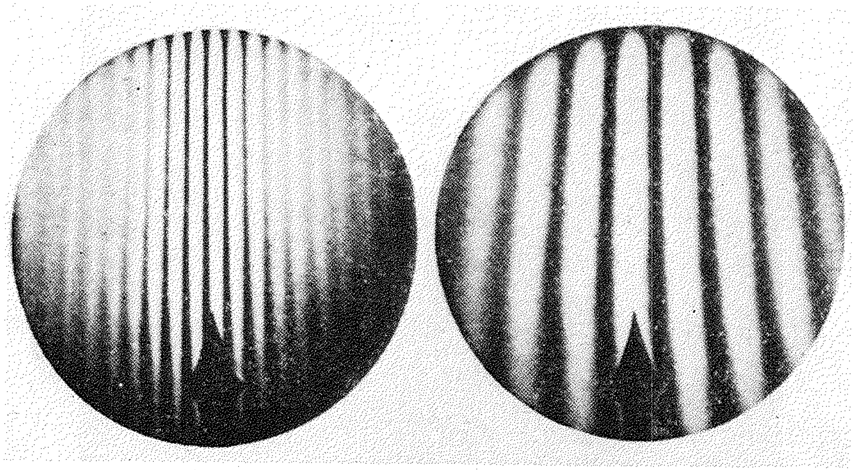
Fig.21. The experimental arrangement.



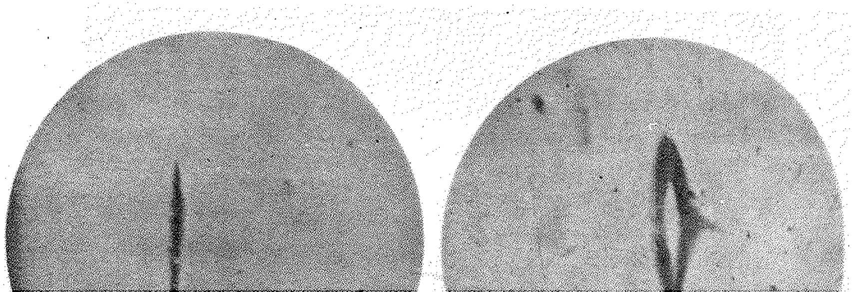
connected with the signs of the Zodiac, the metals had been related to astrological theories and were thought to have powers of a rather special kind. So gold, as the supposedly most perfect metal, began to assume an importance over and above its role in the economic systems of the time. To find a way of transmuting common metals into gold would then not only be of some economic advantage (even in the ancient world not everyone had fully grasped the folly of inflation), but it would also open up the technical possibility of creating other perfect substances, for instance the perfect medicine, the *panacea*.

Chemists, in this tradition, believed that the metals, like all other substances, were formed from different proportions of the four basic elements. They supposed that if they could find out the proportions in baser substances they could add to or take away from the amounts of the elements which were out of balance, so to speak, and so modify the substance. If they could hit on the perfect balance, then they would have created gold. There were mathematical theories derived from some of the simple properties of natural number sequences, such as magic squares, which suggested that some proportions were well grounded mathematically. The research programme based on these theories, which we call 'alchemy', was a total failure. But in the course of trying to do the impossible, alchemists discovered a great many useful chemical reactions and preparations.

Some time between the Renaissance and the end of the nineteenth century, the whole idea of transmuting the elements, now thought of as the most elementary amongst the ordinary substances of nature, had fallen into disrepute. The exact story of the development and spread of this opinion is not



3 (see p. 119). Photograph of a fringe shift, taken from an article by D. C. Miller in *Reviews of Modern Physics*, vol. 5 (1933), fig. 7.



Ernest Rutherford was born of a Scottish father and an English mother in Nelson, New Zealand, in 1871. His father was a small farmer and something of a general engineer, and his mother was a schoolteacher. He won a scholarship to Nelson College for his secondary education. He excelled at school, particularly in mathematics. Another scholarship took him to Canterbury College at Christchurch, then one of the constituent colleges of the University of New Zealand, in 1889. He took his M.A. in 1893 with a double First in Mathematics and Mathematical Physics. He had already begun research work into magnetism, and in 1894 to 1895 he developed a detector for radio waves.

In 1895 he was awarded an 1851 Exhibition Scholarship to Cambridge, where he worked under J. J. Thomson, in the Cavendish Laboratory. His first studies in Cambridge were in collaboration with Thomson, on the ionization effects of X-rays. Then, in 1898, he turned to the exploration of the phenomenon of radioactivity, the emission of radiation from the natural breakdown of elementary substances.

He was offered the chair of physics in McGill University in Montreal in 1898. Not only did this move give him a laboratory of his own, but put him in the financial position to marry Mary Newton, to whom he had become engaged while at Christchurch. Here he began the astonishingly fruitful collaboration with the eccentric Frederick Soddy, who supplied the necessary chemical expertise, in their joint investigation of the properties of radioactive materials. With Soddy, Rutherford formulated the atomic disintegration theory of radioactivity in 1902. He was elected a Fellow of the Royal Society in 1903 and awarded the Rumford Medal in 1904.

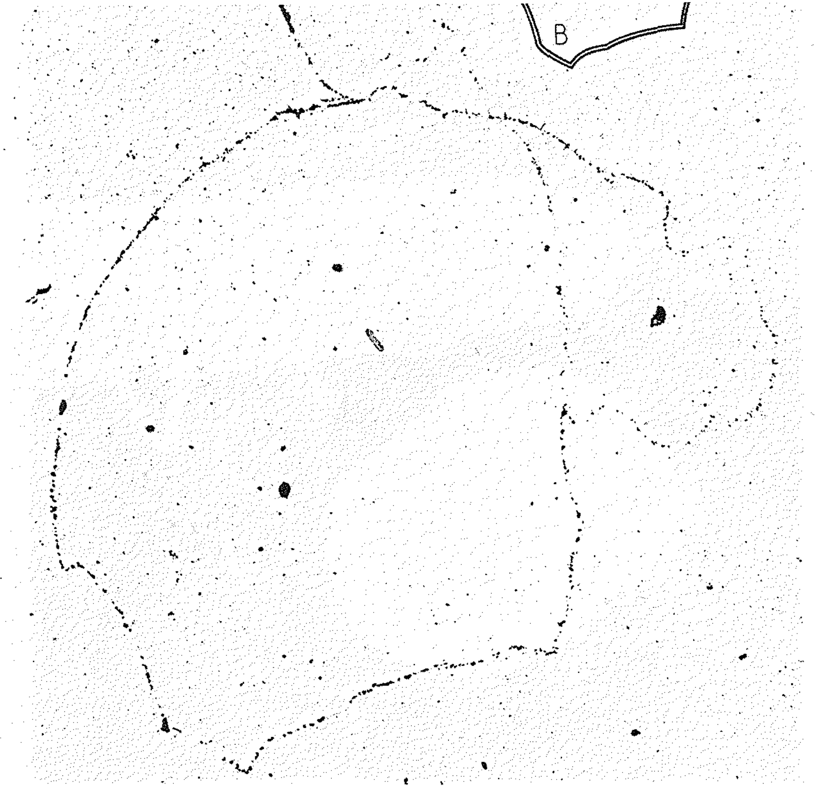
In 1907 he returned to Britain as Professor of Physics at the

19. J. J. BERZELIUS

The Perfection of Chemical Measurement

Jöns Jacob Berzelius was born at Vaversande, Ostergotland, in Sweden, in 1779. His father was a teacher, but died while Berzelius was still an infant. His mother married again, but she too died very shortly, and he was brought up by his mother's sister, 'Auntie Flora'. When she married a widower with a young family the boy was not welcome and was sent to an uncle. At twelve he was sent to school at Linkoping, where he largely supported himself by private tutoring. At this time he had a great interest in natural history. But there were troubles at the school. He was not as diligent as he should have been, and left, perhaps at the suggestion of the school authorities. In 1796 he began medical studies at Uppsala. He was very fortunate to be able, at least for a time, to learn chemistry from A. G. Ekeburg, an excellent teacher and a chemist of repute, who had discovered titanium. However, he was forced to withdraw from these studies since he could not afford the course.

The financial crisis was solved by his uncle who apprenticed him to a pharmacist, and then to a physician at a health spa. During this time he learned the techniques of quantitative analysis. Part of the mystique of the spa cures was to advertise

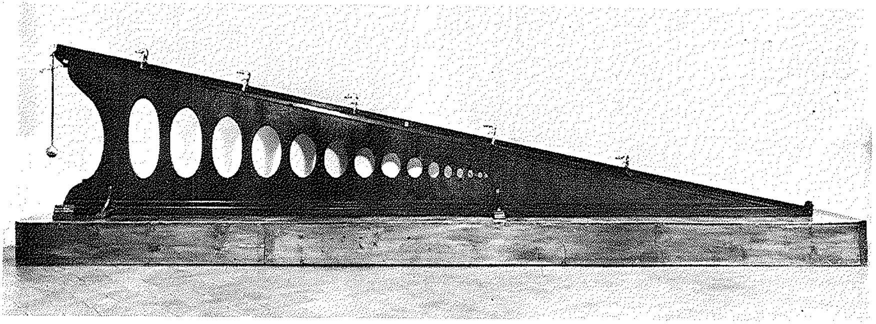


5 (see p. 131). The splitting of a ring of DNA of the bacterium *Escherichia coli* strain K12 (Hfr♂), starting at X and dividing at Y. The chromosome is about two-thirds replicated, XBY and XAY being the daughter replicas, and XCY being the parental double helix.
Reproduced from Hayes, *The Genetics of Bacteria and their Viruses*, 2nd edn, New York (1976), plate 27.

constituents 'molecules'. For instance, if one supposed that the weight of an atom of sulphur was thirty-four times that of an atom of hydrogen, and found that in a sample of hydrogen sulphide 0.04 grams of hydrogen had combined with 0.68 grams of sulphur, one could conclude by simple arithmetic that the proportion of hydrogen and sulphur atoms in hydrogen sulphide was 2:1.

Berzelius was greatly disenchanted with the inaccuracy and inadequacy of the methods of analysis in use in his day. He had started to write a textbook of chemistry for the cadets at the Military Academy and for medical students. When he tried to bring some order and system into the existing quantitative data he found not only confusion but downright contradiction. When results were coordinated across a variety of compounds, inconsistencies appeared. The atomic theory, as elaborated by Dalton, placed strict requirements on the relationships between elements. If a given weight of an element A combines with a certain weight of element B, and the same weight of A combines with so much by weight of element C, then there should be a definite relationship between the weights of B and C when they combine. They should either be in the same ratio as they each bear to A, or some integral multiples of those weights. This allows for the possibility of there being different numbers of atoms of B and C in combination when they combine with each other, from when each combines with A. But Berzelius found it impossible to make existing results of measurements of relative weight fit in with these requirements. So began his obsession with precise measurement. He realized by about 1810 that progress in chemistry needed a new kind of experiment, one of meticulous, painstaking accuracy. Only then could reliable hypotheses about the atomic constitution of

1 (see p. 62). Lorenz being followed by three hand-reared imprinted Greylag Geese.



2 (see p. 71). A replica of Galileo's apparatus, made in 1775 for the Grand Duke of Tuscany. Istituto e Museo di Storia della Scienza, Florence.

autobiography Berzelius notes, 'many times I had to repeat my analysis with different methods to find that method which was most certain to give the correct result', that is the result in accordance with the atomic theory. Berzelius did not *discover* that the elements combined in integral proportions. By assuming that that was indeed the way they must combine he corrected and improved and adjusted his experimental technique until his results were in accordance with this principle.

The analytical programme

The secret of his success was a kind of perfectionism, an obsession with accuracy. 'My first attempts in this were not successful,' he says. 'I still had no experience regarding the great accuracy that was needed, nor how a greater accuracy could be obtained in the final results.' The answer to these troubles lay in attention to detail. Equipment had to be designed so that there was as little loss of material as possible. In reactions which required pouring the vessels had to have lips that discharged the very last drop. Filter papers not only had to have a standard residue of ash, but it was advisable to wet them before they were to be used, to prevent some of the substances dissolved in the solute being absorbed by the fibres of the paper. But above all the manipulative technique had to be precise. It consisted in 'observing a large number of small details which, if overlooked, often spoil several weeks of careful work'.

Atomic weight determinations depended on two things. It was necessary to know the relative numbers of atoms of different elements in compounds, for instance, whether an oxide was ZnO or ZnO_2 or Zn_2O and so on. It was also became very depressed in his old age. 'God knows', he said, 'what happens to your time once you have begun to get old. You are busy all the time, you do important things, you work, and yet when you sum it all up the result is nothing.' He died in 1848.

Analytical chemistry before Berzelius

In 1810 the study of chemistry had run up against a serious inadequacy in its empirical methods. Dalton had proposed, generalizing both brilliantly and wildly from very rough data, that when elements combined to form compounds they did so atom to atom, so to speak. Allowing for the differences in weight between the atoms of distinct elements, this combining principle leads to the hypothesis that there should be simple and fixed ratios between the amounts of constituent elements that go to form a particular compound. The basic structure of the reasoning behind all the analytical work of the period can be illustrated as follows: if sodium hydroxide is formed by the combination of clusters of atoms in which one atom of sodium combines with one of oxygen and one of hydrogen, and sodium atoms are 23 times as heavy as hydrogen atoms, while oxygen atoms are 16 times as heavy as hydrogen atoms, then in any sample of the compound the weights of sodium, oxygen and hydrogen ought to be in the ratios 23:16:1. Working backwards one ought to be able to compare a great many compounds to guess the unit weight of the atoms of elements. Then, by dividing the weights of each element found in an analysis of a compound by the relative unit weight of atoms, one can find the atomic constitution of the most elementary units of a compound. We have come to call these compound molecules it was natural to think of hydrogen as a monoatomic gas. If one thinks of the ultimate particles of hydrogen as atoms, single Hs, when as we now think they are really molecules, H_2s, pairs of atoms, one will be inclined to take $2H = 1$ as the standard, and this is just what Berzelius did. Correcting the value gives us an atomic weight for chlorine of 35.47, relative to hydrogen.

From the point of view of scientific method it is worth noticing Berzelius's devotion to the 'intensive design'. There are two ways of gaining general knowledge by experiments. One can study a great many samples and then find their typical properties by some sort of averaging. This is called the 'extensive design'. Or one can take one, or at most a very few cases, and assume that they are typical. Their properties will then be the defining properties of all samples similar to them. This is called the 'intensive design'. As MacNevin says of Berzelius, 'The selection of the proper method of analysis seemed far more important to him than the frequent repetition of the measurement common today . . . he seldom repeated any of it once completed and was ready to defend its reliability.'

By 1818 Berzelius was ready to announce the atomic weights of 45 of the 49 known elements. Throughout his life he continued to improve and extend these results.

Berzelius was not just a superb experimenter. He developed, in much the same way as had Davy, an electrical theory of chemical combination, but with a more detailed and precise form. Soderbaum, quoted in Jorpes, gives Berzelius as saying, 'Atoms contain both types of electricity, these being placed at different poles in them, but one type is dominant. Affinity is due to the effect of the electrical polarities of the particles. Thus, all compounds are composed of two parts, these parts

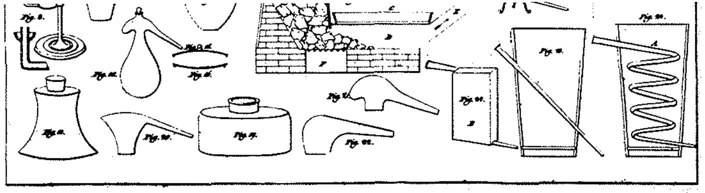


Fig.35. Some examples of Berzelius's apparatus. Illustration from the original Swedish edition of the *Treatise on Chemistry,* vol. III, plate I.

these English chemists, and he knew also of Gay-Lussac's successful demonstration that when gases combined chemically, they did so in integral ratios of volumes, so that water was formed by the combination of two volumes of hydrogen to one of oxygen. At that time, it must be remembered, the familiar distinction between atoms and molecules had not been formulated. Contemplation of all these matters led Berzelius to the conviction that equal volumes of permanent gases (those which could not then be liquified) must, at the same temperature and pressure, contain equal numbers of atoms. There must then be a relation between the integral ratios of volumes and the integral ratios of weights, revealed in studies of chemical combination. This notion was later to be incorporated in more refined form into chemistry as Avogadro's Hypothesis. Incomplete though these ideas proved to be they were sufficient to give Berzelius a powerful enough theoretical basis for his purposes, a theory which foretold that combining weights must be in integral proportions. This enabled him to formulate the idea of a 'correct' measurement.

A measurement was correct when it gave integral proportions, for that was required by the atomic theory. In his

In 1886 Crookes first put forward the idea that the elements as we know them may be mixtures of yet more elementary substances, the masses of the atoms of which were related to the mass of oxygen atoms in integral proportions, more or less as Prout had suggested. But this idea was not experimentally verified until F. W. Aston developed the mass spectrograph. By developing J. J. Thomson's magnetic and electrical field equipment by which he had studied the physical properties of electrons (see Experiment 16), Aston was able to separate atoms of the same electrical charge but different mass. Previously these had been taken to be all of the one kind, *the* atoms of neon, say. The confusion had arisen because it turned out that the chemical behaviour of atoms was largely determined by their electrical properties and very little by their mass. Aston showed that elements of even atomic number, that is having an even number of electrons in their atoms, tended to form two isotopes (as they came to be called). These each had nearly integral weights, and the traditional atomic weight, so carefully computed by Berzelius, was the result of a mixture of isotopes. Different elements were found in nature to be made up of different proportions of their isotopes. This was why even that paragon of accuracy, Berzelius, had found the atomic weight of chlorine to be that awkward number 35.47 (adjusted to the modern hydrogen standard).

In these experiments we see the refinement of a measuring technique. But 'refinement' is correlative to the idea of 'correct result'. Without some prior conception of how things ought to go, we can have no idea of a correct or an incorrect result. With the help of atomic theory Berzelius was able to anticipate his experimental results, using theory to correct experiments.

If the atomic proportions are known by comparison with other analyses it is a simple matter to calculate the ratios of the atomic weights. For instance, if the oxide consists of two atoms of oxygen to one of the metal then the above ratio must be divided by 2.

Here is Berzelius's description of the steps involved in finding the atomic weight of chlorine relative to oxygen and to hydrogen. In his *Treatise on Chemistry*, volume V, he says, 'I established its [chlorine's] atomic weight by the following experiments: (1) From the dry distillation of 100 parts of anhydrous potassium chlorate, 38.15 parts of oxygen are given off and 60.85 parts of potassium chloride remain behind. (Good agreement between the results of four measurements.) (2) From 100 parts of potassium chloride 192.4 parts of silver chloride can be obtained. (3) From 100 parts of silver 132.175 parts of silver chloride can be obtained. If we assume that chloric acid is composed of 2 Cl and 5 O, then according to these data 1 atom of chlorine is 221.36. If we calculate from the density obtained by Lussac, the chlorine atom is 220 [relative to the atomic weight of oxygen]. If it is calculated on the basis of hydrogen then it is 17.735.'

The simplicity of the reasoning and the need for careful manipulation are vividly illustrated in this passage. To get to the final ratio between the element in question (chlorine) and the standard (oxygen), several different ratio determinations have to be gone through, each of which must be as accurate as possible. Berzelius's result is in good agreement with modern determinations, but for one thing. It is only half the modern value. The reason lies in the way the hydrogen standard was computed. Without the distinction between atoms and

B

The Power and Versatility of Apparatus

Manipulative care is but one side of the story of technique. The other is to be told in terms of the ingenuity, fruitfulness and power of the apparatus with which experiments are finally actually conducted. It is only too easy to think of an experiment in purely logical terms, particularly if one's knowledge of experimentation comes from reading the finished products of an investigation, the scientific paper or textbook. Sometimes a whole new field is opened up by the invention of an apparatus of great power and versatility. One of the most successful of such pieces of apparatus was the equipment developed by **Otto Stern** and H. Gerlach for the production and study of molecular beams.

chemical knowledge and technique from all over Europe.

Atomic Weights after Berzelius

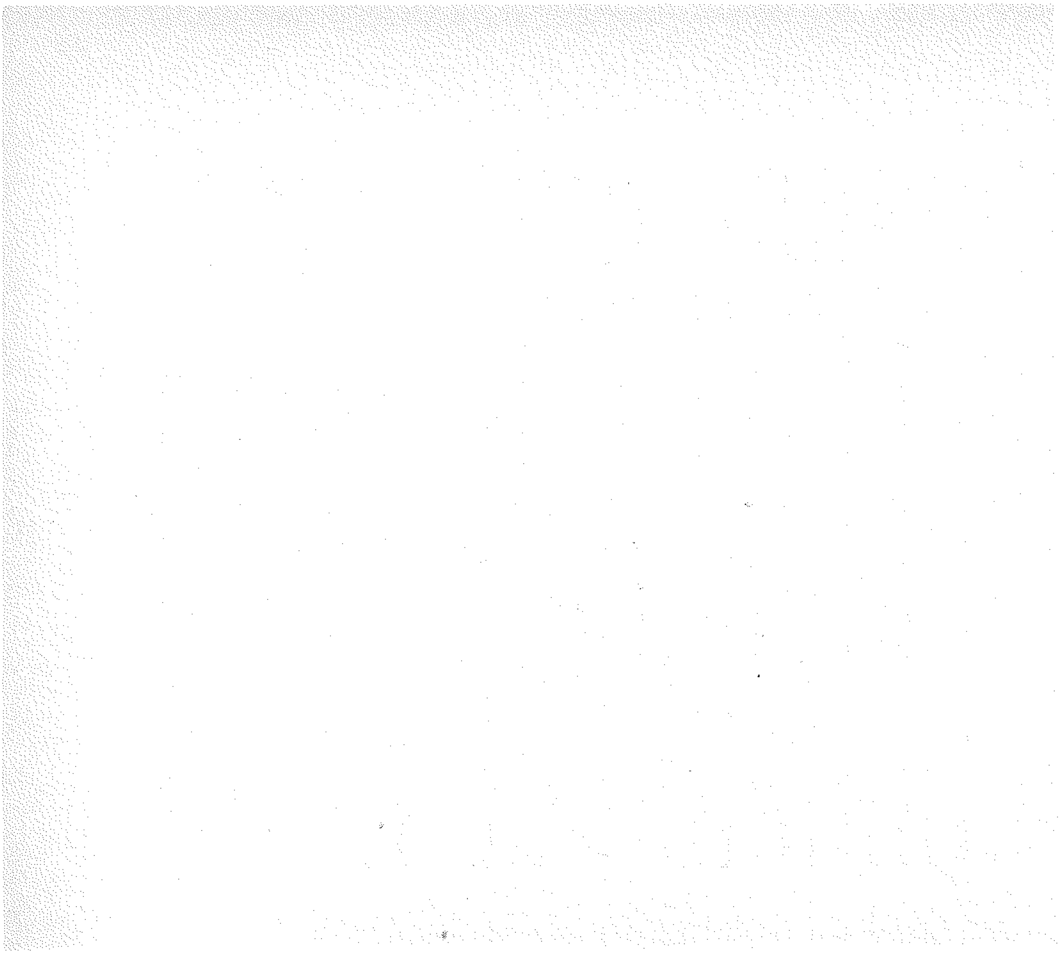
Berzelius's methods depended on the accuracy with which he was able to infer the proportions of each kind of atom in a compound. He was also able to utilize a more direct method for spot-checking some atomic weights. The technique had been perfected by Dulong and Petit. They had been exploring the consequences of Dalton's idea that the heat capacity of the atoms of all gases was related to their relative size. They found that his hypothetical figures were very much in error. In the course of this work they noticed an important relation between atomic weight and specific heat; that is the amount of heat required to raise the temperature of a standard mass of a substance by a standard amount. This relation, verified only for solid substances, later came to be known as their law of atomic heat. It turned out that the product of atomic weight and specific heat of an element was a constant. With the help of Regnault they checked Berzelius's results, and found that some of his figures should be doubled and others halved, for instance the atomic weights of silver and sulphur were wrong. Unfortunately, though their law did allow some direct check on Berzelius's results, it had some exceptions, and was not a wholly reliable guide. But gradually the combination of more and more exact chemical knowledge, a clearer idea of the difference between atoms and molecules, and further refinement of direct measurement techniques cleared up most of the anomalies during the nineteenth century. But it remained to explain why the measured atomic weights were not whole numbers.

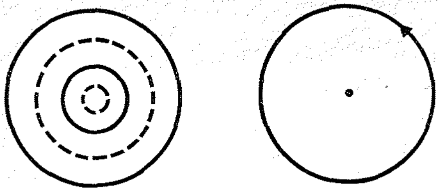
demonstration of the wave-like properties of matter, which, in classical physics, had been assumed to be wholly particle-like. In 1923 he moved to Hamburg to his own laboratory. With new and greater facilities he was able to develop the molecular beam methods still further, and it was there that the actual demonstrations of the wave aspects of matter were achieved.

Stern left Germany in 1933 under the threat of the Nazi regime, and settled in the United States, working at the Carnegie Institute. Unlike some of those driven out by the Hitler government he never did strike the same vein of productive work as he had had to abandon in Germany. He was awarded the Nobel Prize in 1943. In 1946 he retired to Berkeley, California, and died there in 1969.

The context of the experiments

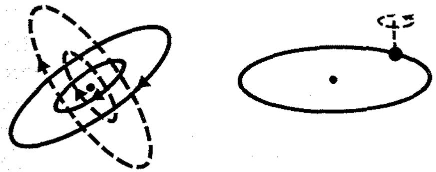
The discoveries which flowed from Stern's development of molecular beam apparatus were relevant to problems which had been formulated almost at the very time that Stern was at work on testing hypotheses of his own contriving. These hypotheses turned out to bear directly on main-stream physics. The electron theory of the atom had been developed by Neils Bohr from hints that had emerged from Rutherford's demonstration of the nucleated form of atoms. If both the positive charge and the bulk of the mass of an atom were concentrated in a small central region or nucleus, then it would seem reasonable to suppose that the remaining mass and the balancing negative charge would be concentrated in the periphery. A natural step was to treat electrons as small charged bodies and to imagine them revolving around the nucleus in some kind of planetary motion. This idea suggested





Quantized orbits

Quantized angular momentum



Quantized orbital planes

Quantized spins

Fig.36. A representation of the meaning of the four quantum numbers.

possible orbits for electrons. The first use of the Stern–Gerlach apparatus that I shall describe was directed to testing whether the idea of introducing a third quantum number, space quantization, was right.

These quantum numbers came from considering electrons as particles and seeing what changes to the traditional principles of mechanics needed to be made to accommodate their peculiar behaviour. But it was already well established that beams of electrons behaved in a very odd way when they interacted with each other. They showed interference effects as if they were waves. They could be diffracted too. This

Otto Stern was born in Schrau, in the province of Upper Silesia, formerly part of Germany, in 1888. His father was a very prosperous grain merchant and miller. The economic security of the family greatly influenced Stern's scientific career. He was the eldest of five children. His primary and secondary education was at Breslau (now in Poland). From 1906 he wandered about the German universities in the fashion of the day, working at Freiburg, Munich and Breslau. As a young man of independent means he was even more free than the majority of German students to indulge his interests, and to work on projects that were not directly related to a career. It was his interest in thermodynamics that drew him back to Breslau where there was a school of physical chemistry, centred on thermodynamic properties of chemical relations. He took a PhD in physical chemistry there in 1912.

In that year he came under the influence of Einstein, doing post-doctoral work with him in Prague and then moving with Einstein to Zurich in 1913. It was Einstein's molecular studies, rather than his relativity theory, that interested Stern. In 1914 he met Max Born, and began to work with him, having been licensed as a *Privatdozent*, an unsalaried lecturer at the university, in that year.

Stern served in the German Army throughout the First World War, but contrived to continue scientific work. For a while he was a meteorologist in Poland, but in the last year of the war was among the scientists seconded to work in Nernst's laboratory in Berlin.

It was after the war that he developed his molecular beam methods for studying free atoms, on the analogy of light beams. His beams of atoms, upon which the experiment described in this section depended, were the basis of his

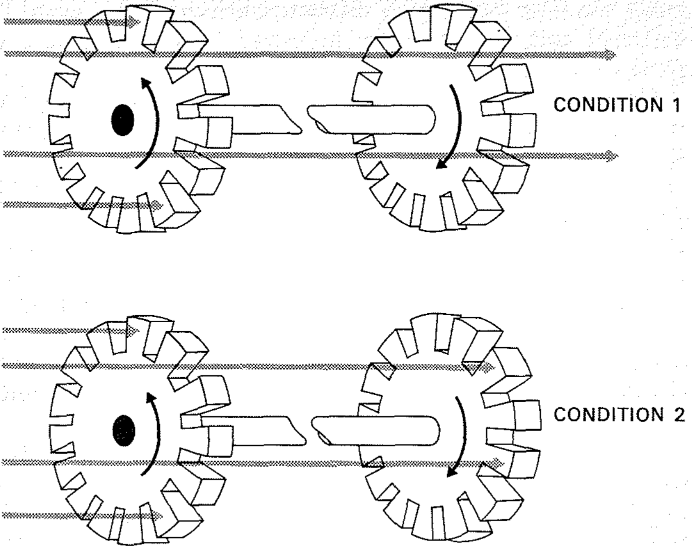


Fig.37. The arrangement to separate out atoms moving at the same speed.

running the gauntlet of the two wheels will be of roughly the same speed.

Similar ingenuity was shown in their development of the second part of the equipment, the high-density magnetic field. The atoms are passing very swiftly through the system, so for there to be any discernible effect, say a splitting of the beam by virtue of the mysterious property of space quantization, the field must be very concentrated. By forming one pole as a knife edge, and the other as a groove and contriving that the beam given out as light of a definite wave length.

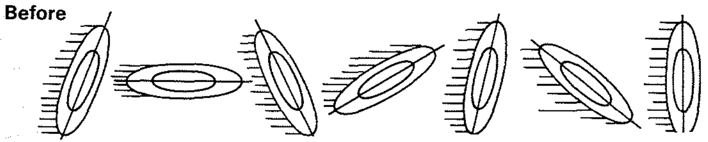
Further study of atomic phenomena suggested that there should be a second quantum number. Electrons seemed not to have just any angular momentum, but to orbit only with certain definite velocities. This feature of the structure of atoms was represented by a letter l. l could be related to n, since the admissible angular momenta were represented by only those integral values of l that lay between 0 and $n-l$.

Would the same kind of feature be revealed for the other major properties of planetary motions, the orientation of the orbital planes and the direction of spin? Would it turn out that the orbits of electrons could be only in some definite planes? Would spin too turn out to be, as physicists came to say, 'quantized'? To represent these possibilities, two further quantum numbers were proposed; m was introduced to represent 'space quantization', the permissible angles that the planes in which electrons orbited could make with some fixed plane, such as a magnetic field imposed from outside. A fourth quantum number, s, was added to represent the possibility that electrons could spin only clockwise or anticlockwise relative to one fixed axis. This has come to be called 'spin up' or 'spin down'. It seemed that all the properties of the electrons that mattered could be expressed by the use of these four quantum numbers.

One might ask why the architecture of atoms should be represented by numbers. It is very easy to see why this should be in the case of the layout of the orbits of electrons around the heavy nucleus. If, in the lowest orbit, an electron has energy e, an electron in the next possible orbit will have an energy $2 \times e$, in the next $3 \times e$, and so on. The numbers 1, 2, 3 and so on are the values of n, the principal quantum number, and define the quantized one way with respect to the plane of their orbiting electrons moving away one way, and those quantized in the other angle moving off in the other way. And that is exactly what Stern found.

The demonstration of the wave nature of matter was equally direct. Experiments by Elsasser, and Davisson and Germer had shown that electrons could be diffracted, apparently a proof of their having some wave-like modes of behaviour. But this was rather a special case and could not be taken as evidence for a general matter–wave equivalence. Electrons no doubt had the peculiar character, behaving like material particles in one kind of set-up and like waves in another. But helium atoms are relatively lumpish and commonplace bits of matter. If they showed diffraction effects, then de Broglie's idea for a thoroughgoing equivalence between matter and waves was much more firmly established.

For this range of experiments the equipment was permuted. The beam-producing equipment with its contra-rotating wheels was used to be sure that all the atoms were at the same speed. The beam-producer was coupled with a lithium crystal for a target, and with a detector to measure the angle through which atoms were diffracted. If they were being mechanically reflected, behaving as a stream of particles, as tennis balls do when reflected off a volley board, then the angle of reflection would be about the same as the angle of incidence. But if they were being diffracted, behaving like a wave, then there should



The importance of Stern's experiment is obvious in the context of the development of physics. But it illustrates another point of interest in studying experiments, namely the power of some techniques to provide answers to a number of different questions, sometimes not fully formulated when the equipment was first developed.

The Stern–Gerlach apparatus is based upon the permutation of three pieces of sub-equipment; there is a device for preparing a beam of molecules (or atoms) all with nearly the same velocity; then there is an arrangement for producing an intense and steeply 'graded' magnetic field, changing greatly in intensity over a very small distance; and finally there is the use of metallic crystals to provide gratings suitable for the diffraction of wave motions of wave-lengths which bodies of atomic dimensions would have, if the De Broglie laws defining the characteristics of associated waves were correct.

To prepare a beam of suitable atoms Stern (with his assistant, Gerlach) used a small crucible, at high temperature, into which samples of the appropriate substances were passed. A narrow slit opened into a vacuum and so, with the heat to provide the thrust, a beam of atoms was produced. But these were of all sorts of energies (velocities). To stop all but those of a very narrow range of velocities they adapted the idea used by Fizeau to measure the velocity of light. The problem is created by the very high speeds of the atoms. If two wheels are fitted on the same axis, both with slits in them, and set to contra-rotate, only those atoms which take just the time for one slit to be replaced by another, to cross between the wheels, will be able to pass right through. So all atoms which do succeed in

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by the quantum theory, then the associated magnetic field of each atom will be associated with that plane. So when an external magnetic field is allowed to affect the atoms they should take up quite definite orientations to that field, depending on their internal magnetic fields.

If there were space quantization, as I have described it in the previous subsection, the orientations of the little magnets, as we are now to imagine the atoms, will not be at random, 'all round the clock', so to speak, but in the particular case Stern was investigating, at *two* distinct angles to the external magnetic field, as predicted from the calculation for the third quantum number. Each orientation corresponds to one of the Pl.4 planes in which electrons might orbit, and so if we look at the image of the beam with the field switched off we should find a single blur on the photographic plate. But when the field is switched on the beam should separate into two, those atoms

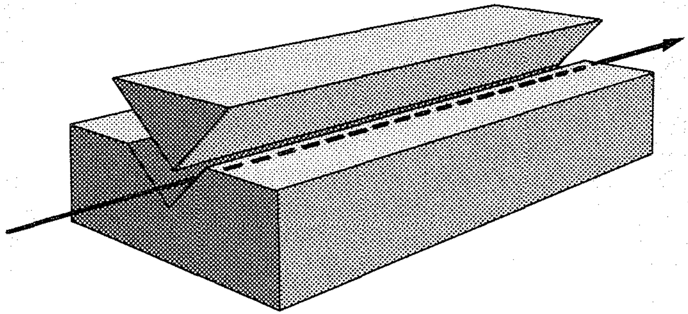

Fig.38. The pole pieces of the electromagnet inside the Stern-Gerlach apparatus.

Index of Names

Developments after Stern and his collaborators

Molecular beam laboratories proliferated as Stern's pupils began to have pupils of their own. The equipment has been greatly refined, new ways of detecting the effects of the beams on different kinds of materials have been developed. But it can be said that in this field, though much ingenious work has been done, the essentials were achieved by its originator, Otto Stern himself.

Even so convincing a series of demonstrations of the particle nature of subatomic matter as were given by Thomson and Rutherford may be upset by new concepts. De Broglie's extraordinary generalization of his rules to all material things suggested the possibility of wave-like effects even for relatively massive bodies like whole atoms. The consequences of the discovery of just the kind of effects his generalization suggested have not yet been fully absorbed into the metaphysics of natural science.

Further reading

The original papers are in German and are to be found in *Zeitschrift für Physik*, 9 (1922), pp. 349–52, a paper by W. Gundlach and O. Stern; and in *Zeitschrift für Physik*, 61 (1930), p. 95, in a paper by I. Estermann and O. Stern.

Estermann, I. (ed.), *Recent Research in Molecular Beams*, a collection of papers dedicated to Otto Stern, on the occasion of his 70th birthday, New York–London, 1959, pp. 1–7 ('Molecular Beam Research in Hamburg, 1922–1933').

Schonland, B., *The Atomists, 1805–1933*, Oxford, 1968, ch. 11.

Losee, J., *A Historical Introduction to the Philosophy of Science*, 2nd edn, London, 1972. Theories of the very nature of science as a mode of knowing about the world have changed along with the changes in science itself. These changes are systematically treated in relation to the history of philosophy and of science.

Magie, W. F., *A Source Book in Physics*, Cambridge, Mass., 1963. Most of the important discoveries in physics are represented in this collection, made up in the same fashion as the chemistry source-book.

Medawar, P. B., *Pluto's Republic*, Oxford, 1982. This collection of essays contains a marvellous account of the uses of the imagination in scientific discovery.

Singer, C., *A History of Biology*, London and New York, 1960. Emphasis is placed on the interaction between changing ideas of life and living function and the slow growth of anatomical, physiological and historical knowledge of living forms.

Singer, C., *A Short History of Scientific Ideas to 1900*, Oxford, 1959. This is still the most clearly written and comprehensive history of science available.

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