Sir Benjamin Collins Brodie (1817-1880)

by William H. Brock

The English chemist Benjamin Collins Brodie, who was regarded by Kekulé as "definitely one of the most philosophical minds in chemistry" (R. Anschütz, *August Kekulé*, Berlin, 1929, I, p. 187), was the eldest son of Britain's leading physiologist and surgeon, Sir Benjamin Collins Brodie (1783-1862). Brodie *père*, who was president of the Royal Society from 1858 to 1861, had been made a baronet in 1834 for his medical services to the Royal family, and his son inherited the baronetcy in 1862. A theist and anti-materialist, Brodie senior was profoundly interested in metaphysical questions. He published two volumes of *Psychological enquiries* (1854 and 1862), a series of dialogues between a country gentleman, a doctor and a lawyer, that were much influenced by Humphry Davy's posthumous *Consolations in travel* (1830). These well-meaning, but turgid, dialogues were concerned with unfashionable topics such as dualism, natural theology, and the problems of pain and immortality. They seem to have made little impact on Brodie's contemporaries, who were finding Herbert Spencer's psychological and evolutionary writings more exciting. However, their publication suggests that the younger Brodie was brought up in an atmosphere of philosophical inquiry in which the metaphysical foundations of scientific beliefs were critically questioned.

The younger Brodie was educated at Harrow School from where he won a classics scholarship to Caius College, Cambridge. However, his father, preferring him to be educated as a commoner, sent him to Balliol College, Oxford in 1835. There, under the influence of the mathematical physicist Baden Powell, his interests turned away from classics to mathematics. He also attended chemical lectures given by Charles Daubeny in the basement of the Ashmolean building opposite Balliol. Brodie graduated in 1838, but because of his refusal to assent to the 39 Articles of the established Church of England, he was unable until 1860 to obtain the M.A. degree essential for a respectable academic career at Oxford and he was always denied a College fellowship. For some time after graduation Brodie trained for the bar at Lincoln's Inn in the chambers of an uncle. In 1844, however, he met Justus Liebig as a guest in his father's house and immediately abandoned the law to

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study chemistry at Giessen, where he was awarded a doctorate in 1850 for the analysis of beeswax (*Annalen der Chemie und Pharmacie*, **67** [1848], 180-214; **71** [1849], 144-170). This work, for which he gained the Fellowship of the Royal Society (1849), as well as its Royal Medal (1850), proved the existence of solid alcohols that were homologous with known alcohols, and it had important implications for the understanding of animal metabolism.

In the decade following his return to England, Brodie worked in his own private laboratory in Albert Road, near Regent's Park, where he taught chemistry to his friend and later Oxford mineralogical colleague, Nevil Story Maskelyne (Vanda Morton, *Oxford Rebels*, Gloucester, 1987). In 1847 he joined the Royal Institution (RI) as assistant to William Brande (a close friend of his father's), where he came into contact with Michael Faraday whose negative views on atomism must have greatly influenced him. In 1844, Faraday had rejected atomism because of the conundrum why, if it contains more atoms per unit volume, is potassium hydroxide a non-conductor, whereas potassium, with fewer atoms, is a conductor? (L.P. Williams, *Michael Faraday*, London, 1965, pp. 576-8). On Brande's retirement in 1853 Brodie hoped to succeed him and to transform the RI into a research institution on the Liebig Giessen model, but he was strongly opposed by the managers who disapproved of the 'advanced' and unpopular character of his lectures.

By 1850 Brodie had established himself as a leading experimental and theoretical chemist. Alan Rocke has classed him as one of the circle of modernizers who accomplished the "quiet revolution" of systematically basing the construction of both inorganic and organic molecules on two volumes of hydrogen, a view principally propelled in London by Alexander Williamson at University College and August Hofmann at the Royal College of Chemistry during the 1850s (*The Quiet Revolution* University of California Press: Berkeley, 1993; and *Nationalizing Science*, MIT Press: Cambridge, MA, 2001). Brodie's early chemical work, which was implicitly atomistic, was an attempt to reconcile Berzelian electrochemical dualism with the most recent Gerhardtian ideas concerning the self-combinations of atoms (*i.e.* two-volume formulae for H_2, Cl_2 *etc.*). He was intensely interested in allotropy, which he believed to be due to the arrangement and electric charges of the particles making up an element. He discovered that iodine catalyzed the conversion of yellow into red phosphorus, and that pure graphite, when treated with potassium chlorate, formed a crystalline graphitic acid, which he speculated might contain a graphite radical, $(Gr)_4$ or *graphon*. His process for the purification of graphite, which he patented, proved of considerable technical value. From 1850 to 1856 he was Secretary of the Chemical Society, and while its President, 1859-1861, he was one of the British delegates to the conference on molecular weights in Karlsruhe.

In 1855, despite considerable opposition from theological Fellows, Brodie succeeded Daubeny as professor of chemistry at Oxford, where he did much to gain recognition for chemistry as an academic study, as well as proper laboratory facilities for its teaching. He had long been friendly with an influential group of Broad Church dons like Benjamin Jowett and Arthur Stanley who, however, disapproved of his atheistic tendencies (E. Abbott and L. Campbell, *Life and Letters of Benjamin Jowett*, London, 1897). Another Oxford influence was Richard Congreve who (like Williamson) had studied with Auguste Comte in Paris and espoused the cause of Positivism in Britain (W. M. Simon, *European Positivism in the Nineteenth Century*, Ithaca, New York, 1963). Exposure to positivist thought in Oxford, together with his atheistic tendencies regarding revealed religion, Faraday's dismissal of atomistic explanations, and Laurent's and Gerhardt's espousal of the unity of chemical theory based on rational and systematic language (M.P. Crosland & J.H. Brooke, "Gerhardt", in: *Dictionary of Scientific Biography*, vol. 5, pp. 369-75), all seem to have caused Brodie to conclude that atomism was leading chemists astray.

At the beginning of the 1860s Brodie turned his back on the structuralist tendency of organic chemists such as Williamson and Adolph Wurtz and professed a determined skepticism towards the truth and conventional utility of the atomic theory. His sustained opposition to Dalton's atomism during the last twenty years of his life proved the most remarkable philosophical and theoretical achievement of his career. As a positivist dedicated to the removal of the metaphysical from science he strongly objected to the realism implied by the availability of molecular models made of balls and wires that contemporary instrument makes had placed on the market following the symbolism introduced by Alexander Crum Brown and Edward Frankland. Brodie's position was that the ultimate nature of matter was unknowable; chemistry had to be based solely on observational phenomena. For Brodie, influenced by his reading of Lavoisier, Condillac, Gerhardt, and Comte, atoms were an unnecessary and confusing interpolations between observation and expression of phenomena because they were not subject to any rules and invited the unwary to think of chemical phenomena in terms of real balls. He denied that the object of science was to explain. He agreed with Gerhardt that "chemical formulae are not meant to represent the arrangements of atoms, but rather to make evident simply and exactly the relations that link bodies during transformations" (*Philosophical Transactions*, **156** [1866], 781-859; **167** [1877], 35-116). We cannot ask what water is, but only describe how it behaves and what it becomes during interaction with other chemical materials. Because we have no way of grasping the underlying reality of things, we must be content to describe accurately how matter behaves. Since Daltonian-Berzelian atomism had led chemists astray, atomism and its symbolism had to be swept away. The facts of chemistry were to be represented by suitable symbols that could be derived algebraically from Gay Lussac's law of volumes and Dulong and Petit's law of specific heats. Further algebraic manipulation of the symbols might then lead to new truths. "Such a system", he claimed, "is based, in the most absolute sense, upon fact, for it presents only two objects to our consideration, the symbol and the thing signified by the symbol, the object of thought and the object of sense".

In 1866 the Royal Society began to publish Brodie's "The Calculus of Chemical Operations" (*Philosophical Transactions*, **156** [1866], 781-859; **167** [1877], 35-116) which introduced Greek symbols for the chemical elements to replace the roman alphabet (Berzelian) symbols that contemporary chemists used to represent atomic weights. Brodie's symbols, however, represented *operations* on space (volumes), not weights for, besides its revolutionary symbolism, the calculus also demanded an appreciation of George Boole's algebraic logic, which Brodie had studied after the publication of Boole's *Investigation of the Laws of Thought* in 1854. In this an equation such as $y = xy$ is a symbolic statement that y is a subset of x in which the symbol x is an operator on y. Although professional mathematicians like William Donkin and Henry Smith later advised Brodie, it appears that he developed the system without professional help. The principal difficulty about the calculus for the present-day historian and philosopher of science is the need to explain it before going on to discuss it and the difficulty of giving any concise description of it. The best secondary sources are still those by W.V. Farrar (*Chymia*, **9** [1964], 169-79) and Duncan M. Dallas (in W.H. Brock, ed., *The Atomic Debates*, Leicester, 1967, pp. 31-90). There are collections of Brodie manuscripts at the University of Leicester and at the Oxford Museum of History of Science.

Boole had developed the concept of symbolic operators in algebraic analysis. These provided a code as to how the symbols were to be understood and manipulated. Brodie exploited this in the idea of a chemical operator, or chemical operations, that he symbolized by Greek letters. It is probably unwise, therefore, to interpret Brodie's philosophy as analogous to Percy Bridgman's later operationism. He proposed that if two substances with the empirically-derived weights, x and y combined to form a new compound with weight xy, then $x + y = xy$. From such weight equations he constructed a symbolic algebra that bypassed any atomistic interpretation. Aware from recent chemical history that an absolute standard of comparison was required, he chose for volumes the liter, which he defined as a unit of space (analogous to Boole's universal set). A choice of standard element was also required, and like Dalton he chose hydrogen. However, he defined it (α) as having a simple weight of one – in other words he did not allow it to be distributed in chemical operations (reactions). In molecular terminology, his standard was $H = 1$, and not $H_2 = 1$. The assumption meant that all elements of odd valence have to be symbolized by a combination of prime factors, one of which is α. Thus chlorine is $\alpha\chi^2$, *etc.* For non-vaporizable elements, Brodie made use of Dulong & Petit's rule, together with additional assumptions. The resultant system generated three kinds of elementary symbol: (1) those like hydrogen and mercury expressed by a single symbol, *e.g.* α; (2) those like oxygen and sulfur expressed by identical symbols, *e.g.* ξ^2; and (3) elements such as the halogens that appeared to be a combination of the first two groups, *e.g.* $\alpha\chi^2$. Brodie justified the simple assumption that hydrogen was undistributed by arguing that it predicted the law of even numbers, whereas an assumption that hydrogen was α^2 did not (though it was compatible with the law). Contemporary chemists were quick to point out that if hydrogen was allowed a compound weight, α^2, then all the Greek symbols would become formally identical to those of Berzelian atomism (*viz.* $\alpha^2 = H_2$). In this light, the question of the Proutian complexity of the elements became something of an *experimentum crucis* for the calculus.

Few contemporary chemists were able to follow Brodie's mathematical reasoning and what principally interested them was its implication that elements like chlorine might be compounds that contained hydrogen. The new spectroscope appeared, at first, to promise validation of Brodie's prediction. His "ideal chemistry", as he called it, stimulated a great deal of fruitful controversy in the 1860s and 1870s, but it ultimately foundered because of his inability to account for the phenomena of structural isomerism and stereoisomerism. Both properties and methods of preparation distinguish isomers; but in the calculus methods of preparation are unimportant, as long as the same compound results. Although Brodie struggled with probability theory, his notation refused to yield a simple method of differentiating isomers – something that was brilliantly elucidated by le Bel and van't Hoff using the model of chemical structure based upon an atomic theory of matter. Nor, as it transpired, did Brodie's three groups of elements (differentiated by the form of their symbolism) bear any analogy to the groupings produced by the periodic law.

Brodie resigned from Oxford in 1872 because of ill-health, and retired to a magnificent house on the top of Box Hill in Surrey. In the same year he published a paper on the action of electricity on oxygen which confirmed by the calculus suggestions that the ozone molecule was triatomic, and introduced the well-known apparatus for the preparation of ozone, "Brodie's ozoniser". He died at Torquay on 24 November 1880 from rheumatic fever, with the calculus on which he had spent twenty years of his life uncompleted.

Farrar saw Brodie as the Don Quixote of chemistry, tilting his mathematical lance against the windmill of atomism. Although a chemical *cul de sac*, Brodie's calculus of operations nevertheless remains of interest to historians and philosophers of chemistry for at least five reasons.

(1) His methodological use of the thought experiment. Thus, in seeking support for the possible existence of unknown primitive elements such as χ (which spectroscopy might reveal in the sun), he imagined a country called Laputia where carbon could not be isolated because experiments could only be conducted between 0°C and 300°C. Yet, in using

the calculus of operations, the Laputians might speculate that carbon existed from the derivation of the symbol $\alpha\kappa^2$ from the reduction of two units of methane to three units of hydrogen and one of acetylene. Brodie was keen to use thought experiments to support the compound nature of chlorine, $\alpha\chi^2$.

(2) Normalization. In order to classify and factorize chemical equations (the burden of Part II of the calculus published in 1877), Brodie had to 'normalize' his equations with respect to space. He did this simply by adding a numerical factor (representing units of empty space or null sets). Such mathematical manipulations of equations were not to appear in chemistry again until the advent of quantum chemistry. Brodie can be seen to be a pioneer in believing in the possibility of finding mathematical solutions to chemical problems.

(3) Mechanisms of reactions. Although fellow chemists and type theorists such as Williamson had begun to study how organic reactions worked, Brodie seems to have been the first to state explicitly how his symbolism helped explain the likely mechanism of an operation. Given the relative simplicity of Brodie's Greek symbolism, it was easy to 'see' the shifts and substitutions that were taking place. (In fact, of course, it is possible to factorize molecular equations, which, in effect, was what the Crum Brown-Frankland structural formulae notation made visible.)

(4) Brodie's identification of "chemical equations [as] a study of transcendental interest" insofar as they yield new truths. It is only recently that what Klein has called "paper chemistry" and chemical formulae as tools and instruments have received attention by chemical philosophers (Ursula Klein, *Experiments, Models, Paper Tools*, in press; *Die Sprache der Chemie*, ed. P. Janich, N. Psarros, Königshausen & Neumann, Würzburg, 1996). Brodie's claim to have no model involved in his form of paper chemistry seems to cry out for further attention.

(5) Comparison with other chemical iconoclasts who rejected atomism. Half a century after Brodie, the Bohemian metallurgist František Wald (1861-1930) suggested a kind of formal operationsim based upon the phase rule, though he does not seem to have been aware of Brodie's calculus (Britta Görs, *Chemischer Atomismus*, ERS Verlag, Berlin, 1999, pp. 186-93).

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