OSBORNE REYNOLDS, 1842—1912.

Osborne Reynolds was born August 23, 1842, at Belfast. He came of a clerical family. His grandfather and great-grandfather had been rectors of Debach-with-Boulge, Suffolk. His father, the Rev. Osborne Reynolds, was thirteenth Wrangler in 1837 (a year remarkable as being that of Green and Sylvester), and was subsequently Fellow of Queens' College, Principal of the Belfast Collegiate School, Headmaster of Dedham Grammar School, Essex, and finally, in his turn, rector of Debach.

For his early education Reynolds was indebted chiefly to his father, first at Dedham and afterwards privately. In 1861, at the age of nineteen, he entered the workshop of Mr. Edward Hayes, mechanical engineer, of Stony Stratford, in order, as Mr. Hayes expressed it, "to learn in the shortest time possible how work should be done, and, as far as time would permit, to be made a working mechanic before going to Cambridge to work for Honours."

The motives which guided the first steps in Reynolds' career may be stated in his own words.* "From my earliest recollection I have had an irresistible liking for mechanics; and the studies to which I have specially devoted my time have been mechanics, and the physical laws on which mechanics as a science are based. In my boyhood I had the advantage of the constant guidance of my father, also a lover of mechanics, and a man of no mean attainments in mathematics and their application to physics." After referring to the year he spent with Mr. Hayes, he proceeds:—"Having now sufficiently mastered the details of the workshops, and my attention at the same time being drawn to various mechanical phenomena, for the explanation of which I discovered that a knowledge of mathematics was essential, I entered at Queens' College, Cambridge, for the purpose of going through the University course, previously to going into the office of a civil engineer." The decision to proceed to Cambridge appears to have been taken rather suddenly, for his previous education had not included Greek; he succeeded, however, by the obstinate labour of a few weeks, in reaching the standard of the "Previous Examination." His mathematical studies were pursued with success, for he graduated in 1867 as seventh Wrangler, and was immediately afterwards elected to a Fellowship. He then entered the office of Mr. John Lawson, civil engineer, of London. In 1868 he was elected to the newly instituted professorship of engineering in the Owens College.

This professorship was almost† the first of its kind in England, although similar chairs had existed for some time in Scotland and in Ireland, and had been illustrated by such names as those of James Thomson and Rankine. It is possible that Reynolds was influenced to some extent by

* Taken from his letter of application for the Owens College professorship.

† Fleeming Jenkin had been appointed professor of civil engineering at University College, London, in 1865.

the tradition of these chairs. With Rankine, at all events, for whom he always professed the greatest admiration, he had strong affinities, in the range of his scientific interests, in the directness of his intuitions, and in the courage and tenacity with which he attacked difficult and complicated problems. He resembled Rankine also in his views as to the scientific character of the training to be given to engineering students. The course of instruction which he arranged for his pupils, and to which he consistently adhered, was remarkable for the thoroughness and completeness of the theoretical groundwork. On one point he was uncompromising. In his mind all engineering was one, so far as the student is concerned, and the same fundamental training was required whatever the nature of the specialisation which was to come afterwards in practice. As an ideal principle this can hardly be gainsaid, although the varied ramifications of mechanical science, and the increasing multiplicity of "subjects," have in more recent times compelled a deviation from it. The course laid out by Reynolds was no doubt felt by many students to be severe, and there is testimony that his lectures were not always easy to follow. It is therefore hardly to be wondered at if at first some shade of disappointment was felt by the eminent practical engineers, and other friends of the Owens College, who had worked for the creation of the professorship. Few could have foreseen at that time how splendidly the appointment was destined to be justified, not only by the distinguished scientific career for which it served as a base, but also by the succession of students who derived stimulus and inspiration from the genius of their teacher, and who came afterwards to occupy important positions in the professional as well as in the academical world. Both branches of his activity were greatly assisted by the establishment of the Whitworth Engineering Laboratory in 1888, although some facilities for hydrodynamical experiments on a moderate scale had been secured at an earlier date. Several of the more important appliances in the new laboratory, *e.g.* the triple-expansion engines and the hydraulic brakes, were specially designed by Reynolds for purposes of study and research, and presented many novel features.

Shortly after his appointment Reynolds entered on the career of original research which continued without interruption down to his retirement in 1905. The results of many of his investigations were communicated in the first instance to the Manchester Literary and Philosophical Society, which cherished the memory of Dalton, and was still distinguished by the presence of Joule. In the affairs of this Society Reynolds took a lively interest; he was Secretary from 1874 to 1883, and President for the term 1888–9. After the death of Joule he wrote for the Society a memorial volume, which was published in 1892; and he was the leading spirit in the movement for a public monument to Joule, which resulted in the beautiful statue by Gilbert which now adorns the Manchester Town Hall.

His scientific writings are a remarkable fulfilment of the plan traced out in the letter which has been quoted. They deal almost entirely with mechanical questions, or with physical phenomena so far as these appear to be susceptible of mechanical interpretation. Although they treat of subjects which are at first sight widely different in character, there are many underlying affinities, and trains of thought which constantly recur. It is characteristic of Reynolds that, even when they bear on questions of immediate practical import, there is a persistent endeavour to penetrate to fundamental principles, and to disregard what is accidental or adventitious. It is probably for this reason, in part, that there was some delay in the recognition of his work by the practical world, even in cases where his ideas have since been proved to contain the germ of fruitful applications. His work on turbine pumps, for example, is now recognised as having laid the foundation of the great modern development in these appliances, whilst his early investigations on the laws governing the condensation of steam on metal surfaces, and on the communication of heat between a metal surface and a fluid in contact with it, stand in a similar relation to recent improvements in boiler and condenser design.

About the year 1899 the Cambridge University Press suggested to Reynolds that a collected edition of his papers would be valuable, and offered to undertake the publication. This signal compliment on the part of his old University was greatly appreciated by him, and in due course two considerable volumes appeared. Some idea of the extent of his scientific activity may be gathered from an inspection of the list of contents of this edition. In the way of practical papers, we find, in addition to those already referred to, investigations on the "racing" of the screws of steamers, on the steering of screw steamers, on rolling friction, on the errors of indicator diagrams, and on the action of tidal currents in the silting of estuaries. These, and others, may still be read with profit, and display, equally with the more impressive contributions to science, his skill in unravelling and explaining a mass of complicated detail by the light of some simple mechanical principle.

In the scientific world at large, however, the reputation of Reynolds is most likely to rest in the future on his contributions to general physics, and, in particular, to hydrodynamics, although here also the suggestion came usually from some practical question of engineering. The paper on "Lubrication" (1886), for example, explains on familiar hydrodynamical principles how the presence of a film of oil is maintained between a rotating shaft and its bearings, in spite of enormous pressures between them. The explanation, when given, is almost obvious; but Reynolds was the first to formulate it explicitly, and to submit it to the test of calculation. To many minds it had not even occurred that there was anything to be explained at all.

In the paper "On the Law of Resistance in Parallel Channels" (1883), an experimental investigation is made of the circumstances which determine whether the flow of water through a pipe shall be smooth and regular, with a resistance varying as the velocity, as in Poiseuille's experiments with capillary tubes, or irregular and sinuous (or "turbulent," to use Lord Kelvin's happy description), with a resistance varying more nearly as the square of the velocity, as in most questions of practical hydraulics. The conclusion, based on the dynamical principle of "dimensions," and confirmed by the experiments, is that there is a certain "critical velocity," depending on the ratio of the (kinematic) viscosity of the fluid to the diameter of the pipe, at or about which the transition takes place from one type of motion to the other. The character of the motion, at any stage, was revealed by the behaviour of a filament of coloured water introduced into the stream, a device often used by Reynolds in the study of fluid motion. The experiments described in the paper, and often repeated by Reynolds in his lectures, were of a beautiful and striking character. Although much has since been written on the subject, and something still remains to be cleared up, the investigation has taken rank as a classic, and is perhaps the most widely appreciated amongst the decisive achievements of the author.

The most extensive piece of purely experimental work carried out by Reynolds was undoubtedly that bearing on the Mechanical Equivalent of Heat, and described in the Bakerian Lecture for 1897. This was prompted by a number of considerations. The original determination of Joule depended ultimately on the properties of a particular thermometer. More recent observers had endeavoured to refer their measurements to the absolute scale, but with somewhat discordant results. Measurements of the heat generated in the hydraulic brakes in the Whitworth Laboratory had been conducted under Reynolds' direction for some years, and compared with the work absorbed, but this had been done mainly by way of verification, and for practice. He was at length led to recognise that he had at his command appliances which could be used on an unprecedented scale, and to solve a more definite problem. The question which he attacked was to ascertain the total amount of work required to raise a pound of water from freezing point to boiling point, or in other words, the *mean* specific heat (in terms of work) between these two temperatures. The object of the measurement thus became absolutely definite, and independent of any arbitrary thermometric scale; and at the same time, owing to the great quantities which could be dealt with, the margin of error could be greatly reduced. The principle of the method was simple in the extreme; water was fed into the brake at the freezing temperature, there raised by friction to boiling point, and then carried off to a tank on the table of a weighing machine. The work absorbed was given by the couple on the brake, multiplied by the total rotation of the shaft. A good deal of preliminary work was required, and some improvements in the mechanism, before the method was brought to its ultimate degree of accuracy. The final measurements, which extended over a considerable period, were undertaken by Mr. W. H. Moorby. The definitive result was that the mean specific heat between freezing and boiling points, expressed in mechanical units, at Manchester, is 776·94. The whole investigation is a model of scientific method, and may claim to rank among the classical determinations of physical constants.

Among the shorter writings which have played a part in the development of science mention may be made of the papers on the "Refraction of Sound" (1874), and on "Group-Velocity of Waves" (1877). The effect of wind on the transmission of sound had been discussed by Stokes in 1857. Reynolds independently gave the same explanation, and confirmed it by a series of experiments; he also added an examination of the various effects of a vertical temperature gradient, according as the temperature decreases or increases upwards. As regards group-velocity, a geometrical explanation had been given by Stokes, but Reynolds brought in the very important and significant fact that the group-velocity gives also the rate of transmission of energy.

A word must be said as to the style and composition of his papers, if only because these elements have been the occasion of some injustice and neglect. The leading idea is in nearly all cases simple; his bias was, indeed, always to look for a simple explanation of a phenomenon, rather than to frame a theory based on the concurrence of a number of independent causes. But when he came to write out the results of his researches, he appears to have aimed in the first place at a statement which should accurately reflect his own experience of the matter. Unfortunately, the points which have given most trouble to the author are not always those which are most difficult to the reader, and *vice versâ*. When, on one or two occasions, he took up a subject for a second time, with a view to explaining it to a popular audience, he was lucid and forcible. Like some other distinguished physicists whom one can call to mind, he was not a great reader of contemporary scientific literature. When new theories were brought under his notice, he thought the questions out independently and in his own way. He held to his own technical terms and phrases, even when there was an established usage, and sometimes employed familiar terms in a new sense. Consequently, the reader of his papers will at times find it necessary to bring some patience to the task, if he means to extract the solid value which is to be found in them. But, with one or two exceptions, there are no cases of obscurity which cannot be surmounted in this way.

Although he sometimes affected, not quite seriously, to despise mathematics, he had considerable mathematical power, and did not hesitate to apply it on occasion. One or two of his calculations, if isolated from their context, would rank as considerable analytical achievements, even if they had been carried out with the help of modern and more expeditious methods. Reference may here be made to the paper on "Dimensional Properties of Matter in the Gaseous State" (1879), and to that on the "Dynamical Theory of Incompressible Viscous Fluids" (1894). The former paper, written in the early days of the radiometer, is important in relation to the theory of gases, and discusses, both experimentally and mathematically, the new phenomenon of "thermal transpiration." In the latter an attack is made on the very difficult problem of calculating theoretically the critical velocity, already referred to, at which the regular flow of a liquid through a pipe becomes unstable.

At the British Association meeting of 1885, Reynolds read a short paper on the "Dilatancy" of granular media. When an agglomeration of loose granules is closely packed, it cannot have its shape altered without increasing, at all events temporarily, the volume of the interstices. Consequently, if such an aggregation is prevented from expanding, it becomes rigid. These principles were illustrated by simple but striking experiments, and it was also pointed out that they lead at once to the explanation of a familiar but hitherto obscure phenomenon, viz. that when a foot is planted on the firm moist sand of the sea-shore, the space immediately around becomes relatively dry, whilst the space beneath the foot, when this is raised, is found to be abnormally wet. This explanation, it may be mentioned, gave great delight to Lord Kelvin. In spite of the interest of the experiments, Reynolds was careful to state that the theory was anterior to them. He had long speculated on the possibility of a mechanical theory of matter and ether which should, amongst other things, resolve the riddle of gravitation. He had convinced himself that a medium composed of smooth rigid grains (*e.g.* spheres) in contact was promising, and it was by reflection on the properties of such a medium that he was led to foresee the somewhat paradoxical behaviour of sand and other granular aggregations which was so beautifully confirmed by his experiments.

The results of the remarkable physical speculation referred to are recorded in the long memoir on the "Sub-mechanics of the Universe" which marked the close of his scientific career. This was read before the Royal Society on February 3, 1902, and now constitutes the third and final volume of his collected papers. Unfortunately, illness had already begun gravely to impair his powers of expression, and the memoir as it stands is affected with omissions and discontinuities which render it unusually difficult to follow. No one who has studied the work of Reynolds can doubt that it embodies ideas of great value, as well as of striking originality; but it is to be feared that their significance will hardly be appreciated until some future investigator, treading a parallel path, recognises them with the true sympathy of genius, and puts them in their proper light.

Prof. Reynolds, owing to the failing state of his health, withdrew from the active work of his chair in 1905. His last years were spent in retirement at Watchet, Somerset, where he died on February 21, 1912. He had been twice married; first, in June, 1868, to a daughter of Dr. Chadwick, of Leeds, who died in July, 1869; and secondly, in December, 1881, to a daughter of the Rev. H. Wilkinson. A son by the first marriage died in 1879. By his second marriage he leaves three sons and a daughter.

The character of Reynolds was, like his writings, strongly individual. He was conscious of the value of his work, but was content to leave it to the mature judgment of the scientific world. For advertisement he had no taste; and undue pretensions on the part of others only elicited a tolerant smile. To his pupils he was most generous in the opportunities for valuable work which he put in their way, and in the share of credit which he assigned to them in cases of co-operation. Somewhat reserved in serious or personal matters, and occasionally combative and tenacious in debate, he was in the ordinary relations of life the most kindly and genial of companions. He had a keen sense of humour, and delighted in starting paradoxes, which he would maintain, half seriously and half playfully, with astonishing ingenuity and resource. The illness which at length compelled his retirement was felt as a grievous personal calamity by his pupils, his colleagues, and by other friends throughout the country.

He was elected a Fellow of the Royal Society in 1877, and received a Royal Medal in 1888. He was made an Honorary Fellow of Queens' College, Cambridge, in 1881, and received the degree of LL.D. from the University of Glasgow in 1884. An admirable portrait by Collier, presented by scientific friends and admirers from all parts of the kingdom, hangs in the hall of the Manchester University.

H. L.