Teaching Quantum Physics in Cambridge: George Birtwistle's two books on Quantum Physics.

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Introduction

Shortly after the end of the Great War, Charles Galton Darwin, a former student in Trinity College, Cambridge, and then fellow and lecturer at Christ's College, wrote a letter to his friend Niels Bohr complaining about the situation of the quantum theory in the old university. From his point of view, "physics and applied mathematics here are in an awful state. I am doing my inadequate best to talk to people about quanta; everybody accepts them here now (which is better than it was in 1914 at any rate), but I don't think most of them realize their fundamental importance or have studied the arguments in connection with them … There are plenty of very intelligent people, only under the blighting influence of studying such things as strains in the ether, they none of them know what it is worth doing".[1]

By 1927 things had changed. The Mathematical Tripos (MT) and the Natural Science Tripos (NST) not only included a number of courses on quantum matters, but students taking these subjects were expected to respond questions that, only some months earlier, had troubled the best scientific minds. To give an example, in the spring of 1928, one of the questions in the final exams was the following: "Shew how the Heisenberg matrix of a q-number is determined from the normalised Schrödinger characteristic functions (Eigenfunktionen) of the problem concerned. Illustrate it by the problem of the rigid rotator (molecule)".[2] This question expected an understanding not only of Heisenberg's and Schrödinger's theories of quantum mechanics, but also their equivalence, all of which had been developed only two years earlier. Some students in Cambridge were, thus, at this stage, quite up-to-date with contemporary quantum questions, enabling them to become actors *tout court* in the developments of the new physics.

How did this change come about? The development of quantum physics and early quantum mechanics is a story that skips Cambridge and, generally, the British world. The first main English actor, Paul A. M. Dirac, appears on the stage only in the second half of the decade of the 1920's. In the background, people like James H. Jeans, Ralph H. Fowler, and Charles G. Darwin play only secondary roles in the grand narrative of quantum physics. However,

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[1] *Archive for the History of Quantum Physics*, Darwin to Bohr, 30.05.1919, microfilm BSC 1, 4. MENTION THE 1919 EXAM!

[2] Cambridge Tripos Examination Papers, 1928.

these and other characters are instrumental to understand how the theory came and took roots in Cambridge.

Here, I want to contribute to the early history of quantum physics in Cambridge by paying attention to the pedagogical side of this story. In particular, I want to concentrate on two books written by a quite unknown Cambridge don, George Birtwistle (1877-1929). This senior wrangler (1899) was fellow and lecturer of mathematics at Pembroke College and lectured on quantum physics and quantum mechanics between 1924 and 1929, producing two books that compile his lectures. These two books reflect a number of interesting aspects: first, they help us understand the way a generation trained in the old wrangler tradition could understand and teach quantum theory; second, they characterise the contents that non-specialists in Cambridge received about the new physics; and, third, they embody the tensions experienced by lecturers and students of the quantum theory at a time when this was developing and transforming at high speed.

In the first section I will refer to the early responses to quantum physics by British scientists. The 1913 BAAS meeting in Birmingham was the first major public event in Britain in which positions in favour and against the theory of the quanta were discussed at large. James Jeans, one of the first British *converts* to Planck's theory, wrote a report on the *status quo* of the quantum. This short book eventually became the source from which many British physicists got their first knowledge on quanta during and immediately after the War. In the second section, I shall explain the evolution of teaching quantum theory in Cambridge: courses, examinations and lecturers. This will introduce us to the two books by George Birtwistle, *The Quantum Theory of the Atom* (1926), and *The New Quantum Mechanics* (1928), in sections 3 and 4, respectively. These two books may be channels to understand the situation of the quantum in the Cambridge lecture room: undergraduate students had up-to-date resources, locally produced, with which to keep up with the latest developments in quantum physics and quantum mechanics. But, as we shall see, some of these resources were not necessarily the best tools to grasp the radical novelty of the new theories.

1. James Jeans and his "Report on Radiation and the Quantum-Theory"

The first written reference to Planck's hypothesis in the British scientific media was probably Joseph Larmor's explicit rejection in the BAAS meeting of 1902. In the following years, the general attitude in Britain ranged from total opposition to oblivion but was, more generally, one of scepticism. Ten years later, however, and after the first Solvay Conference in 1911, the increasing presence of Planck's hypothesis in the scientific literature forced a discussion on the topic in the same forum: the BAAS meeting, in Birmingham, in the summer of 1913. James Jeans, who had recently converted to the theory of the quantum and was one of only two British physicists present at the Solvay meeting, took on board the task to explain and defend the theory of the quanta to a reluctant audience.

Jeans had been second wrangler in 1898, being one of two students, together with G.H. Hardy, to first attempt the Cambridge Mathematical Tripos in only two years—and not in the usual three years—after which he was appointed fellow and lecturer of Trinity College.[3] During these years, he worked on radiation theory and statistical mechanics, producing his first book, *The Dynamical Theory of Gases*,[4] and contributing to what we now know as the Rayleigh-Jeans law for the distribution of radiation of a black-body, derived from the equipartition of energy. His constant failure to describe the experimental energy distribution of black-body radiation using classical arguments did not force Jeans, at first, to accept Planck's hypothesis, but to search for alternative mechanisms to explain the experimental law. Faithful to the equipartition principle, central in statistical mechanics, Jeans was first willing to challenge Planck's law on the basis that real, physical equilibrium was impossible in a black-body. But by 1910, he had changed his mind, forced by the experimental success of Planck's law as well as by the theoretical proof that this law could be obtained *only* with the assumption of quanta.[5] Another recent convert, Henri Poincaré, also developed a very detailed demonstration of the sufficiency and necessity of the hypothesis of quanta to obtain Planck's law in 1912, just after the first Solvay conference. Jeans admired Poincare's more general proof, and he used it in his subsequent defence of the quantum theory.

The *Report on Radiation and the Quantum-Theory* that Jeans prepared for the 1913 BAAS meeting, and which was published a few months later, acted as a sort of textbook from which many British scientists learnt the basic tenets of the quantum theory during the War, and immediately after.[6] That is why it serves as the starting point in this pedagogical story, although it was not formally a textbook. This *Report* is also a window open into Jeans' own *conversion* process, emphasising the impossibility to account for black-body radiation with no other hypothesis but Planck's quanta and, also, stressing the importance of Poincaré's reflections and Bohr's model of the atom. Einstein's explanation of the photoelectric effect, and the theory of the specific heats of solids by Einstein, Debye and Lindemann are also present, but only as indirect support to the quantum hypothesis.

The book is an interesting exercise of rhetoric to convince British mathematical physicists, mostly influenced by the MT Cambridge tradition, of the unavoidability of the quantum hypothesis. From the beginning of the book, he addresses the same criticisms against Planck's theory that he himself had held a few years before, by acknowledging that "the mere discovery that a phenomenon is difficult to explain in the Newtonian way is no adequate reason for abandoning a system of laws which is known to hold throughout vast regions of natural phenomena. (…) From demonstrating that a matter is difficult to proving that it is impossible is a long step, but if this step can be taken with respect to the explanation of even one well-established phenomenon of Nature, then the logical necessity of rejecting the impossibility becomes unanswerable".[7]

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[3] For a biography of James Jeans, see Milne, E. A., *Sir James Jeans, a Biography*, Cambridge, 1952.
[4] Jeans, J., *The Dynamical Theory of Gases*, Cambridge, 1904; (2nd ed., 1916).
[5] A detailed account of Jeans' process can be found in Hudson, R., "James Jeans and Radiation Theory", *Studies in the History and Philosophy of Science*, 20, 1989, 55-77.
[6] Jeans, J., *Report on Radiation and the Quantum-Theory*, London, 1914; (2nd ed., 1924). For its impact, see Milne, *Sir James Jeans*, p. 17; and McCrea, W., "How Quantum Physics came to Cambridge", *New Scientist*, 11, 1985, p. 58.
[7] Jeans, *Report*, p. 2.

The tendency in Britain at the time was to follow after Joseph Larmor's steps, who was still trying to obtain Planck's law in terms of some continuous motion or mechanism, in spite of Jeans' and Poincare's demonstration of its fundamental impossibility.[8] For instance, professor Augustus E. H. Love, second wrangler in 1885 and Sedleian Professor of Natural Philosophy in Oxford since 1898, argued that "from a mathematical point of view there must be infinitely many formulae which would agree equally well with the experiments".[9] Larmor himself, and also J.J. Thomson, were the main opponents to Jeans, this time also rejecting the new theory of specific heat in solids, while Lorentz and a young Niels Bohr were on Jeans' side. The discussions at the Birmingham meeting of the British Association "made it abundantly clear that the quantum-theory is far from being regarded as inevitable yet by many of the English school of physicists",[10] and that is why Jeans wrote the *Report* with a very pedagogical approach, including full references to the criticisms by Love, Thomson, Larmor and others, and his answers to those challenges. Incidentally, the BAAS meeting started with a presidential address given by Oliver Lodge on "Continuity", a manifesto in favour of the real existence of the ether, its essentially continuous nature, and against the theories of Relativity and quanta.[11]

To understand the *Report*, thus, we have to bear in mind the mental framework of the public to which it was addressed, a framework that Jeans himself had until very recently fully shared, and which has its roots in the metaphysics embedded in the training of Cambridge mathematical physicists. The ether was a real substance—and this remains so in the *Report*—, and physical explanation was synonymous with mechanical modelling. These two aspects remain practically unaltered, as is clear already in the introductory chapter:

> "For whatever is regarded as certain or uncertain about the ether, it must be granted as quite certain that it approaches more closely to a continuous medium than to a gas … And if, as seems most probable, the ether is a perfectly grainless structure, … the total energy [in a black-body] will be infinite … To put the matter shortly: in all known media there is a tendency for the energy of any systems moving in the medium to be transferred to the medium and ultimately to be found, when a steady state has been reached, in the shortest vibrations of which the medium is capable. This tendency can be shown (Chapter II) to be a direct consequence of the Newtonian laws. This tendency is not observed in the crucial phenomenon of radiation; the inference is that the radiation phenomenon is determined by laws other than the Newtonian laws".[12]

As a materialisation of this statement, chapter 2 partly repeats Jeans' own work before 1910, when he tried to exhaust all possible mechanisms that might account for the "full

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[8] Larmor, J., "The Statistical and Thermodynamical Relations of Radiant Energy", *Proc. Roy. Soc.*, 83, 1909, 82-95. See Hudson, "James Jeans and Radiation Theory", p. 72.
[9] Love, A.E.H., "Discussion on Radiation", BAAS Report, 1913, p. 384. This discussion is also reported, with some complementary information, by P.P. Ewald in the Physikalischer Zeitschrift, 14, 1913, 1297-1302. I thank Massimiliano Badino for pointing at this fact.
[10] Jeans, *Report*, p. 23.
[11] Lodge, O., "Presidential Address", BAAS Report, 1913, pp. 3-42. Lodge's Presidential Address is also a manifesto in defence of spiritualism, psychic research, and a certain unity of Nature with the Creator.
[12] Jeans, *Report*, pp. 6-7.

radiation" or "black body radiation" with classical arguments. The core of the argument was, obviously, that "any radiation formula corresponding to a steady state must be derived by expressing that the amount of energy gained by the ether is equal to the amount absorbed", for which one had to think of different possible mechanisms of absorption and emission. Jeans tried with three such possibilities: "resonators" of perfectly definite periods, the motion of free electrons in matter, and the photo-electric effect.[13] In all cases he obtained the Rayleigh-Jeans formula he had obtained from the general principle of equipartition, and, therefore, he inferred that the ultraviolet catastrophe was unavoidable on classical grounds: "It is to escape from this necessary consequence of the classical mechanics that the quantum-theory has been brought into being".[14]

Chapters 3 to 6 give a very clear account of the quantum-theory and its success to account for radiation, spectra, the photo-electric effect, and the specific heat of solids (in this order), leaving for the last chapter what he calls the "physical difficulties" or the "physical basis" of the theory.[15] And this is the chapter to which I now turn, because it is here that we find Jeans trying to understand or, better, to speculate on the physical implications of accepting the quantum-theory. Because, as he well says, accepting Planck's hypothesis tells us very little about the reality of the physical processes:

> "The indications are that there is, underlying the most minute processes of nature, a system of mechanical laws different from the classical laws, expressible by equations in which probably the quantum-constant *h* plays a prominent part. But these general equations remain unknown, and at most all that has been discovered is the main outline of the nature of these equations when applied to isochronous vibrations".[16]

The main problem was, for Jeans, not that the quantum-theory was, so far, limited in its applicability, but that "even if the complete set of equations were known, it might be no easy task to <u>give a physical interpretation of them, or to imagine the mechanism</u> from which they originate".[17] I emphasise the last sentence because for him, as much as for most physicists of the Cambridge school, intelligibility involved the possibility of imagining a mechanism that could account for the observed phenomena. But when faced with the quantum, any "attempt to imagine a universe in which action is atomic leads the mind into a state of hopeless confusion".[18]

From dimensional considerations, Jeans underlined that Planck's constant had the physical dimensions of angular momentum, something consistent with Bohr's recent theory for the Hydrogen atom. In any case, "the brilliant agreement … with experiment may indicate that in these cases the angular momentum of the single electron certainly behaves as though it were atomic, but this does not carry us any perceptible distance towards a physical

[13] Cfr. Jeans, *Report*, p. 9.
[14] Jeans, *Report*, p. 23.
[15] Jeans, *Report*, p. 33 and p. 79.
[16] Jeans, *Report*, p. 79.
[17] Jeans, *Report*, p. 79, my emphasis.
[18] Jeans, *Report*, p. 79-80.

explanation of why this atomicity exists".[19] More interesting was, for Jeans, and also from dimensional considerations, the fact that *h* is related to the square of electric charge, more specifically to "the strength of a tube of force binding two electrons. This suggests that the atomicity of *h* may be associated with the atomicity of *e*".[20] As a matter of fact, Jeans reminded the reader that the atomicity of the electrical charge had no basis on Maxwell's theory, and that, so far, "no reason is known why an electron with charge ½e should not exist".[21] And, although the atomicity of the charge did not necessarily involve the quantum-theory, "otherwise the quantum-theory would have been fully developed long ago … there is, perhaps, a hope that the two atomicities may be special aspects of some principle more general than either of them";[22] and this was, inevitably, related to the structure of the ether.

The incorporation of J.J. Thomson's 'tubes of force', a very Cambridge mathematico-mechanical device, is, I think, suggestive of the fact that Jeans was not willing to do away with the Cambridge tradition to which he belonged. As a matter of fact, he regarded Einstein's hypothesis of a quantum as "corpuscles of radiation" comparable to J.J. Thomson's real existence of discrete Faraday tubes. Both constructions could account for the structure of energy exchanges, only that the latter would be in continuity with the older framework. But in both cases there was no hope of reconciling the undulatory theory of light with the quantum-theory, since experimental evidence "seems almost to indicate that both theories are true simultaneously".[23]

The chapter, and therefore the book, finishes with a discussion on the reality of the ether, acknowledging that, on this respect, Continental and British physicists play in different—opposed—arenas. Jeans seems to cling to the reality of the ether, but he relegates it to a second place: the real stumbling block being the contradiction between discrete and continuous theories, both valid for different radiation phenomena. And, with this, the last pages of the book convey a certain amount of pessimism as for the *status quo* of physics. In a free translation from Poincaré's *Dernière Pensées* he says:

> "It is impossible at present to predict the final issue. Will some entirely different solution be found? Or will the advocates of the new theory succeed in removing the obstacles which prevent us accepting it without reserve? Is discontinuity destined to reign over the physical universe, and will its triumph be final? Or will it finally be recognised that this continuity is only apparent, and a disguise for a series of continuous processes? … Any attempt at present to give a judgement on these questions would be a waste of paper and ink".[24]

While chapters 2 to 6 were an active exercise to convince the reader of the inevitability of the quantum hypothesis and its successes, these last pages bring that optimism back to the ground by pointing at the difficulties of interpretation of the quantum-theory. But this is done in a particular way: these last sentences can be interpreted as a way to encourage

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[19] Jeans, *Report*, p. 80.
[20] Jeans, *Report*, p. 81.
[21] Jeans, *Report*, p. 81.
[22] Jeans, *Report*, p. 81.
[23] Jeans, *Report*, p. 89. The Tiger and the Shark was still present and would be so for quite some time
[24] Jeans, *Report*, p. 90.

British physicists to embrace the theory without *à priori* rejecting it on the grounds that it is not 'physical', i.e., mechanical. Furthermore, the fact that these considerations appear only at the end of the book, as a separate chapter, may indicate that, from Jeans' point of view, one could and should accept the quantum-theory without having a full answer to its ultimate physical meaning. Partly following the problem-solving tradition of the Cambridge MT pedagogy, Jeans is more concerned about proving that the quantum-theory solves specific problems rather than to pretend an overall challenge on metaphysical grounds.

2. Teaching Quantum Theory in the 1920s

As mentioned in the introduction, the situation of the quantum theory in Cambridge was far from satisfactory at the end of the War. Jeans himself, when adding a last chapter on quantum theory in his 1920 third edition of *The Dynamical Theory of Gases*, regrets the absence of British scientists in the new science. "This chapter—he writes—can of necessity provide only a very brief introduction into the mysteries of Quantum Dynamics, but I hope it will be of value in stimulating the interest of English-speaking readers in a branch of science of which the development has so far been left mainly to other nations".[25]

One way to record the status and evolution of the quantum in the old university is to have a look, however quick, at the evolution of courses taught to undergraduates. The "advanced" optional courses were normally a reflection of the particular interests of individual researchers, and could give rise to exam questions only in what was known as Schedule B of the Tripos, Part II.[26] As a reminder I should say that, following a tradition going back to the 1860's, physics was, in the 1920's, taught as part of the Mathematical Tripos (as theoretical physics or applied mathematics) and as part of the Natural Science Tripos (which was mainly experimental physics). This meant that both worlds were relatively independent from each other: experimental physics being taught at the Cavendish Laboratory, and mathematical physics by college lecturers. However, the special optional courses were mostly open to both kinds of students.

Who could teach quantum theory in Cambridge? Certainly, not people like Larmor or Thomson who were strongly opposed to it. Nor could Rutherford, whose program was basically experimental. It was young people, both trained in the Cambridge Tripos and converted to the new theory, who could teach quantum physics. And these were, at the beginning of the decade, Charles G. Darwin and Ralph H. Fowler. In a recent paper I have discussed Darwin's early understanding of quantum physics and the evolution of his ideas

[25] Jeans, J., *The Dynamical Theory of Gases*, Cambridge, 1921, preface to the third edition.
[26] According to William McCrea, in his recollections of his undergraduate days in Cambridge, "Apparently anyone could offer to deliver a one-term lecture course. If the appropriate Faculty Board approved, it would be announced in the Schedule B lecture list. This implied that in due time a candidate could declare a wish for there to be questions (probably two) on the course in the examination… If any candidate legitimately included a particular course in his list, the lecturer was responsible for producing the questions; these had then to be approved by the Part II Examiners, who had to arrange the Schedule B papers in such a way that every candidate's chosen subjects were suitably distributed through the six papers. But when it came to the examination any candidate could attempt any questions he liked; he need not confine himself to the topics in the list". McCrea, W., … in Williamson, R., ed, p. 62.

throughout the decade.[27] After his training in the MT, he moved to Manchester, where he learnt experimental techniques related to spectra and radioactivity. There, he also met Niels Bohr in the dramatic years of the development of the atom model using the quantum hypothesis. In 1919, he was appointed fellow of Christ College and started giving the first courses on quantum theory. It is interesting to note that the first such course was only available to NST students, probably supported by Rutherford.

When Darwin left Cambridge in 1922, Fowler began to teach quantum physics, this time in courses open to both triposes. Unlike Darwin, Fowler was self-trained in the theory of quanta and eventually became the catalyst of work in quantum physics in Cambridge, promoting a new generation of quantum physicists by, for example, translating into English many of the key papers that were appearing in German, as well as inviting people such as Kronig or Heisenberg to give lectures in Cambridge. He was also a sort of father-figure for people like Douglas Hartree, Llewellyn H. Thomas, and, of course, Paul A.M. Dirac, all of which made important contributions to the development of quantum physics in the late 1920s. It is also well known that Fowler became a sort of *theorist-in-residence* at the Cavendish, as well as Rutherford's son-in-law.[28]

In the year 1924/1925 we see a turning point in the teaching of the quantum theory in Cambridge. Fowler had been, for two years, giving the only one-term course on the "Quantum Theory of Spectra". But that was not enough now. Quantum physics was advancing and Cambridge started to teach advanced courses. Not surprisingly, it was the young generation that could teach the latest developments, since they had been in close contact with Copenhaguen and some German research centres.[29] Thus, we can find advanced courses taught by Dirac and by Hartree in the second half of the decade; courses that were, especially in Dirac's case, but also Fowler's and Hartree's, reflection of science in the making.

The following is a list of all these courses:[30]

- 1920/21, (NST)
  Darwin: 1st Term, <u>"Recent Developments in Spectrum Theory".</u>
- 1921/22, (MT)
  Darwin: 2nd Term, <u>"The theory of quanta".</u>
- 1922/23, (MT & NST)
  Fowler: 2nd Term, <u>"The quantum theory of spectra".</u>
- 1923/24, (MT & NST)

[27] Navarro, J., "'A dedicated Missionary'. Charles Galton Darwin and the new quantum mechanics in Britain", SHPMP, 40, (2009), 316-326.
[28] Gavroglu and Simoes' paper
[29] Fowler, Hartree, and Dirac were visitors of Bohr's Institute in Copenhagen.
[30] From the Cambridge University Reporter.

Fowler: 2nd and 3rd Terms, "The quantum theory of spectra".

- 1924/25, (MT & NST)

  Birtwistle: 2nd Term, "Introduction to the Quantum Theory";

  Fowler: 3rd Term, "The Quantum Theory. Recent Developments".

- 1925/26, (MT & NST)

  Birtwistle: 1st Term, "Introduction to Quantum Theory"; 2nd Term, "Quantum theory of Spectra"; 3rd Term, "The Quantum Theory. Special Topics";

  Dirac: 3rd term, "Quantum Mechanics (Recent Developments)";

  Hartree: 2nd Term, "Physics of the Quantum Theory".

- 1926/27, (MT & NST)

  Birtwistle: 1st Term, "Quantum Theory",

  Fowler: 2nd Term, "Quantum Mechanics and the Theory of Spectra", 3rd Term, "Quantum Mechanics", (cont);

  Hartree: 2nd Term, "Physics of the Quantum Theory".

- 1927/28, (MT & NST)

  Birtwistle: 1st Term, "Quantum Theory of Spectra", 2nd Term, "The New Quantum Mechanics";

  Dirac: 1st Term, "Modern Quantum Mechanics", 2nd Term, "Modern Quantum Mechanics, (cont.)";

  Fowler: 3rd Term, "Statistical Mechanics, Old and New";

  Hartree: 2nd term, "Physics of the Quantum Theory".

- 1928/29, (MT & NST)

  Birtwislte: 1st Term, "Quantum Theory of Spectra", 3rd Term, "Quantum Mechanics";

  Dirac: 2nd Term "Modern Quantum Mechanics";

  Fowler: 3rd Term, "Selected Problems in Wave Mechanics";

  Hartree: 2nd term, "Physics of the Quantum Theory", 3rd Term, "Physics of the Quantum Theory Cont."

The only ‘outsider’ name in the list of lecturers teaching quantum physics is that of George Birtwistle to whom the rest of this paper is devoted. And I say ‘outsider’ not because he came from some other university, but because he was the only ‘real’ wrangler accepting and spreading quantum physics in Cambridge, which makes him a unique example in trying to understand the ways in which the new theory was ‘received’ in the old Cambridge wrangler tradition.

George Birtwistle is a typical product of the MT tradition. Born in 1877, he arrived in Cambridge in 1895 and was bracketed senior wrangler in 1899. This means that he was a fellow student of James Jeans, only that he took the usual three years to sit for the MT examination. After this, he was appointed fellow and lecturer of mathematics in his own college, Pembroke, where he remained until his sudden death in May 1929. Like many dons of the old school, “it was as a teacher rather than as an investigator that Birtwistle was known, and as a teacher that he played a conspicuous part in Cambridge mathematics”.[31] The short description of his teaching style in the obituary note we find in *Nature* is almost all we have about him:

> “As a lecturer, Birtwistle was admirably clear and easy to follow. He set, in fact, a standard of exposition which made it very difficult for anyone to attract students to any duplicate course. His books are like his lectures—admirable expositions of those sections of the subject with which he deals, written in lecture-room style. He seldom attempts to go deeply into difficult points or to present the subject as a single logical whole. His aim is the lecturer’s aim—to interest the student in the subject, especially in its more outstanding or exciting parts, and lead him on to other more systematic or abstruse expositions”.[32]

What courses did he normally teach? In the annual lists we find him consistently teaching the general introductory courses on “Mechanics” (Statics and Particle Dynamics; Rigid Dynamics) and “Electricity”, and he was among the first to take on board courses on Thermodynamics when these were introduced in the list of elementary courses in 1924. As for his more specialised courses, between 1920 and 1924 he was consistently teaching a one-term course on “Hydrodynamics (motion of solids and vortices in a liquid; waves)”. In the year 1924/1925 he starts teaching an “Introduction to Quantum Theory” while Fowler teaches more advanced quantum matters. In the following years he teaches more courses, from which he finally produces two books: *The Quantum Theory of the Atom* (1926), and *The New Quantum Mechanics* (1928).

3. “The Quantum Theory of the Atom”

The Quantum Theory of the Atom is a window open into Birtwistle’s first courses on quantum physics in the early months of 1925, and in the academic year 1925/1926. It consists of a compilation of those lectures, and it was intended as a textbook for a similar course the following year (1926/1927). As is obvious from his correspondence with the

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[31] Anon., “Obituary”, *Nature*, 123, 1929, p. 881.
[32] Anon., “Obituary”, *Nature*, 123, 1929, p. 881.

publisher, Birtwistle rushed the printing of the book for two reasons: "as you know the subject is changing so rapidly that it would be a good thing to get it out as soon as possible; also so far there is no English book of this kind so far published and I think it will meet a real demand".[33] This book does not try to give a full, consistent, and closed picture of quantum physics, but rather to teach the mathematical apparatus needed to apply quantum physics, as known at the time. That means that the book is organised around the quantisation strategy and its application to those cases for which it works. For the conceptually minded reader, however, the book is disappointingly flat. Contrary to what happened with Jeans' *Report*, and also compared to Bohr's or Sommerfeld's pedagogical works, Birtwistle's book does not enter into many explanations about the 'physical' meaning of the theory; it basically teaches the mathematical way to apply quantum physics to different problems and to show their agreement with experimental data.

But before we go into these and other technical elements, there is an aspect of the book, present especially in the more historical first two chapters, of particular interest. Birtwistle links the history of quantum physics to developments by British, especially Cambridge, scientists. *The Quantum Theory of the Atom* describes precisely that: the quantum theory of the structure of the atom, and this is a story that, according to Birtwistle, has its beginnings in Cambridge: "the modern theory of the structure of the atom is in the first place due to J.J. Thomson" with his discovery of the electron.[34] In this timeline, Thomson's key contributions continued with his model of the atom, and also with his study of positive rays, since the latter was the source for Aston's mass spectrograph and the discovery of isotopes.[35] Birtwistle story on the structure of the atom continues with Rutherford "and his school in which the instrument of the α-particle was used to disclose the nature of the atom" and to propose an atomic model "which is now generally used in theoretical work".[36] This model, for instance, is used to explain the nature of Thomson's positive rays.[37]

In this historical survey, Bohr's 1913 contribution to the atomic model comes only after a detailed explanation of the Hydrogen spectrum and the need to explain Balmer's formula. But Bohr's contribution comes also hand in hand with the work of another Cambridge researcher, J.W. Nicholson, who was working on stellar spectra, and who brought forward, in 1912, an atomic theory in which Planck's constant was interpreted as determining the angular momentum of permissible orbits of the electrons inside an atom.[38] Birtwistle rightly distinguishes between Nicholson's and Bohr's contribution, the former giving only the condition for the angular momentum of an electronic orbit to be $nh/2\pi$, where n is an integer, while the latter gave the "new concept which was to be the key to the solution of the problem of spectra", namely that "the radiation emitted between transitions between

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[33] Birtwistle to S.C., Sept 1926. CUP archives.
[34] Birtwistle, *The Quantum Theory of the Atom*, p. 16.
[35] See Falconer's paper.
[36] Birtwistle, *The Quantum Theory of the Atom*, p. 17.
[37] Cfr. Birtwistle, *The Quantum Theory of the Atom*, p. 17.
[38] Nicholson was a Cambridge graduate, taught mathematical physics at the Cavendish Laboratory, and moved to King's College, London in 1912. For a full account of Nicholson's work and influence on Bohr, see McCormmach, R., "The Atomic Theory of John William Nicholson", *Archive for the History of Exact Sciences*, 3, 1966, pp. 160-184.

two stationary states has a frequency v given by the relation $E - E' = hv$".[39] All throughout the book, however, he keeps the expression "the Nicholson-Bohr condition", meaning the nuclear model with quantised orbits. For the reader, this British-oriented story consolidates the idea that it was the "amazing verification" of Bohr's atomic model that "at once fixed attention upon the quantum theory, which up to then had received sceptical regard from physicists in general".[40]

The third chapter is a sort of compilation of things that are related to the quantum theory but that won't be dealt with in detail in the book. First is the one-page explanation of the mathematics of Bohr's correspondence principle in the version he introduced in his 1918 paper "On the Quantum Theory of Line Spectra".[41] After this rather plain introduction of the correspondence principle, chapter 3 continues with a section devoted to the photoelectric effect, and another section in which he explains Einstein's 1917 deduction of Planck's radiation formula. On the former, there is an interesting indentation regarding the quantum of light: "Einstein's theory of 'light quanta' is not now generally accepted by physicists, but the argument above does not essentially depend upon their existence. All that is necessary is to assume that interchanges of energy between radiation and atoms can only occur in quanta". If we remember that the book was written in 1926, this paragraph is somewhat surprising.

Having established the existence, historical origin, and realm of application of the new theory, the rest of the book is an attempt to train students to the technique of quantisation using a twofold strategy: to provide lots of examples where quantisation is successfully applied, and to show that there is continuity in the methods used in 'classical' and quantum theory. Because, as he sees it, that is the only way one gets hold of the new physics: by using it, rather than by presenting it in a general form or analysing its conceptual or philosophical implications. And this brings me to the main claim of this paper. Birtwistle, a first wrangler in the Mathematical Tripos, tries to teach quantum physics in the same way classical physics was taught in the Cambridge MT tradition: by repetition of examples, by solving specific problems, and by a relatively uncritical embracement of particular mathematical methods.

Once Bohr's theory for the stationary states of the hydrogen atom has been introduced, the next step is to extend the quantum theory towards more complex atoms. Here, he introduces Ehrenfest's adiabatic principle, as a generalisation of the Nicholson-Bohr quantum condition: "The question now arises, what mechanical entity is to be equated to *nh* for more complex systems that that of the hydrogen atom".[42] The answer was given by Ehrenfest who supposes "that the 'entity' which does not change under the influence of the slowly changing external forces must be an 'adiabatic invariant' of the classical theory. This is the 'adiabatic principle' of Ehrenfest, and it requires that only adiabatic invariants are to be equated to *nh* in order to determine the stationary states".[43]

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[39] Birtwistle, *The Quantum Theory of the Atom*, p. 23.
[40] Birtwistle, *The Quantum Theory of the Atom*, p. 24.
[41] Bohr, N., "On the Quantum Theory of Line Spectra", D. Kgl. Danske Vidensk. Skrifter, 8, 1918. ENGLISH TRANSLATION.
[42] Birtwistle, *The Quantum Theory of the Atom*, p. 41.
[43] Birtwistle, *The Quantum Theory of the Atom*, p. 41.

With the generalisation of the quantum condition, Birtwistle starts a series of chapters explaining what he calls the basic "general dynamical theory"; chapters in which he fully shows his condition of wrangler. The variation principle, Lagrange's and Hamilton's equations, the Hamilton-Jacobi differential equation and the ways to solve it, the Keplerian orbit, angle variables, and many other mathematical tools are explained. It would look like a book of mathematics (or classical physics) was it not for the fact that at the end of some sections the "quantum condition" appears. And it appears as purely the mathematical condition that some constant in the equations is equated to nh. Without more ado.

As an example, we can pick chapter 9, on the Stark Effect. After a very short summary of the effect, he says that "the classical theory fails utterly to account for the Stark effect", and immediately develops the mathematics of Epstein and Schwarzschild's solutions. "The dynamical problem to be solved is the motion of an electron due to a Coulomb centre of force and a constant force parallel to a fixed direction. This is a particular case of two centres of force solved by Jacobi by the use of elliptic coordinates", which he explains from an exclusively mathematical point of view. At the end of the process, the quantum condition ($J = nh$) is imposed as part of the mathematical technique, with which the numerical results can be calculated and compared with experimental values. The reader is, thus, lead to believe that quantum physics is in strict mathematical (and, *therefore*, physical) continuity with the old physics, since the mathematical methods and formulas are *almost* the same.

It would be superfluous, in this paper, to give a detailed account of all the chapters. The structure is basically the same: classical calculations in which the quantum condition is brought in as a particular mathematical trick that needs to be implemented in order to get a correspondence with experimental data. In 21 chapters one can never find words such as 'provisional', 'incomplete', 'failed explanation', or anything that indicates that the quantum theory of the atom, as it is, is incomplete or, worse, deficient. It is only in a rushed last chapter, written during what looks like his usual vacation in Norway,[44] that Birtwistle introduces the reader to a list of unexplained phenomena like the anomalous Zeeman effect and the Paschen-Back effect, and to new theories, like the BKS and the new quantum kinematics of Heisenberg. But there is no sense of stress, or crisis, or revolution. There are no value judgements. One gets the impression that everything explained, even in these last chapters, are just steps in the development of the new physics.

Only in the last two pages, and in a statement that *de facto* undermines the whole project of this book, does he say:

"Heisenberg has lately put forward the beginnings of a scheme of quantum-kinematics, which when more developed / should lead to the direct deduction of these quantum theory formulae, without the intermediate use of the classical formulae in each problem considered".[45]

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[44] Letters from Birtwistle to the secretary of CUP in the summer 1926 and 1927.
[45] Birtwistle, *The Quantum Theory of the Atom*, p. 230-1.

Such undermining of the whole book, leads us very naturally to Birtwistle's second book, to which the next section is devoted. But before we do that, I would like to pay attention to the fact that Birtwistle's introductory course to the quantum theory was substituting Fowler's similar course in the previous years. Actually, we also have a window open to Fowler's lessons through L.H. Thomas' complete classroom notes.[46] Obviously, these notes have a spontaneity that Birtwistle's book does not have, and one should compare both documents only with caution; but in any case they show us a very similar content (although with a sensibly different structure), but a totally different style. Fowler was actively working in specific problems in the quantum theory and his lectures contain lots of qualitative explanations, experimental results, and a strong sense of the limitations of the current theory. It is, by far, much less mathematical than Birtwistle's, and mathematical developments go hand in hand with constant explanations of their physical meaning, something which is almost totally absent in Birtwistle's book. His style is closer to the old MT pedagogical system in which students were introduced into problem-solving techniques by repetition of cases. The aim of the lectures was seldom to challenge the *status quo* of the theory, but rather to give an account of how to use the accepted theory. And this is what, as I understand it, *The Quantum Theory of the Atom* is: a work to drill students into the quantisation techniques with a very limited resource to experimental results, and with no critical outlook whatsoever on the limitations of the theories explained.

4. "The New Quantum Mechanics"

Birtwistle wrote a second book on quantum physics, related to his more advanced lectures on recent developments of Quantum Mechanics, the preface of which is signed in Copenhagen in October 1927.[47] From a pedagogical point of view, *The New Quantum Mechanics* is very disappointing. Even in the respectful tone of an obituary, his biographer pointed at this fact:

> "Perhaps the least successful of his books was the last, on modern quantum mechanics. Here, owing to the novelty of the subject and the absence (when Birtwistle wrote) of other more systematic expositions (or indeed of any other exposition), the weakness of this deliberate method becomes more obvious. The book gives rather the impression of a collection of interesting isolated sketches".[48]

The New Quantum Mechanics is precisely that: a collection of the latest developments in quantum theory. In words of another reviewer, "This account is very accurate and contains practically everything that has been done up to the summer of 1927. He gives us, so to speak, original abstracts of the principal papers and allows us a survey of everything that is known. This makes the work not exposition from one point of view, as is Weyl's new

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[46] SHQP, reel 5.

[47] The official list of visitors does not include Birtwistle as a formal visitor to Bohr's Institute. Furthermore, in an epistolary exchange with Bohr, they both regret that they couldn't meet each other in Copenhagen during Birtwistle's visit (from which I infer that his was more of a touristic visit than a research trip). See Peter Robertson, The Early Years. The Niels Bohr Institute, 1921-1930, Copenhagen, 1979, p. 156-8. The epistolary exchange can be found in SHQP, n. 16a.

[48] Anon., "Obituary", *Nature*, 123, 1929, p. 881.

book; it is rather an 'impartial' treatment of the methods of the different schools, with credit given to each for its results".[49] In *Nature*, Fowler spoke of *The New Quantum Mechanics* as one of the best examples of introductory books, an otherwise dangerous genre in the current state of affairs, in which Birtwistle gave "a convenient and faithful but uncritical reproduction of much of the earlier work of the theory".[50]

The first five chapters of this book are a good example of my claims at the end of last section. Birtwistle's 'impartiality' involves a neutral style in which there are no critical analysis of the theories, or their theoretical or experimental limitations. These first chapters introduce the notion of spin, for which he needs to explain the problem with the anomalous Zeeman effect, the Stern-Gerlach experiment or Lande's experimental formula. All of these phenomena were well-known long before 1925, when he wrote *The Quantum Theory of the Atom*. But none of these problems were even mentioned in that book, except for the last chapter. Birtwistle was not training his students in the limitations and failures of a particular theory, but on its successes.

The matter of fact style is clear from the very first sentences of the book: "The origin of the new quantum mechanics was an epoch-making memoir by Werner Heisenberg which contained the new concept which was to lead to the phenomenal developments of quantum mechanics of the past two years". And why was a new theory needed? "For some years before 1925, Sommerfeld, Heisenberg, Lande and Pauli had been grappling with the complex problem of the multiplets and their Zeeman separations", which were only partly solved by introducing *ad hoc* half integers as possible values for the quantum numbers. Yet, again, "a real difficulty too had been met with in the spectrum of neutral helium, where *two* electrons revolve round the nucleus (the simplest many electron problem), all the theoretical results found being at variance with experiment; again in the problem of the 'crossed' fields, where an atom is exposed to the combined action of electric and magnetic fields, fundamental difficulties arose". *Obviously*, in his previous book, Birtwistle never talked about these very 'fundamental' problems, or about the limitations of the now 'old' quantum theory. That was, at the time, the way to solve those problems. It is only now, after a new method has been found, that the limitations of the previous way are relevant: "Heisenberg's new theory however at once led to the formula $(n + \frac{1}{2})\, h\nu$ as the energy of the stationary state of Planck's oscillator, so that half odd integers came quite naturally into the new results".[51]

In the last chapter, Birtwistle tried to summarise his understanding of the latest, yet unpublished, developments coming from Bohr's institute. Returning from his holiday in Norway, Birtwistle visited Copenhagen, but Bohr was not there, since his visit coincided with the Como meeting. Thus, Birtwistle got only second-hand accounts of Bohr's latest views. This was, however, one of the points that Cambridge University Press stressed in the advertising of the book. In a note in *Nature*, we can read that the forthcoming book contains

[49] D.J. Struik, Review on The New Quantum Mechanics, The American Mathematical Monthly, 37, 1930, p. 32.
[50] R.H.F[owler?], "Quantum Mechanics", *Nature*, Supplement, March 1929, p. 363.
[51] G. Birtwistle, *The New Quantum Mechanics*, Cambridge, 1928, pp. 1-2.

“new and hitherto unpublished speculations of Prof. Niels Bohr”.[52] Certainly, the last paragraphs of the book include two footnotes, one referring to the meeting in Como, the other to the recent Solvay Conference. And, ironically, this was the source of the only “research paper” that Birtwistle wrote in his life: a note in *Nature* in which he qualifies the tone of the last chapter. There, we read that “Prof. Bohr points out that the wording of the chapter may create the impression that these [probability] calculations were primarily developed in connexion with the new ideas [of complementarity], whereas they may be said to be characteristic of the whole recent developments of the quantum theory”.[53] Actually, the wording of this note was revised and changed by M. Klein and Bohr himself in Copenhagen.[54] This unfortunate anecdote witnesses to the limited understanding Birtwistle had of the depth of the new Quantum Mechanics and the conceptual, methodological and philosophical debates around it, in spite of his relatively good dominion of the mathematics involved.

A last anecdote about the book comes from William McCrea, who was an undergraduate in Cambridge between 1923 and 1926. Talking about *The New Quantum Mechanics*, he recalled that “it was a remarkable achievement to produce such a comprehensive account of work newly published during the two years before the appearance of the book itself. Hartree described it to me in conversation as the ‘bare bones’ of the subject, but it need not be only medical students who find it useful to have a skeleton for their studies”.[55]

Conclusion

Contrary to Fowler’s or Darwin’s lectures, Birtwistle’s courses are seldom mentioned in the recollections of scientists who studied in Cambridge in the 1920s. That may be due to a number of different reasons. It is possible that some bright students and future major physicists attended his lectures but forgot about them, influenced by the selective memory usual in this kind of recollections. But it is also likely that Birtwistle’s courses were seen, already at the time, only as second best, as courses to be taken only by those wanting to get a feeling of the new theory, but not to master it in order to work on quantum problems. That would explain that, among those scientists who became in some degree actors of the new quantum generation, we cannot find students of Birtwistle (some of them actually remember his elementary lectures in mechanics and electricity, but not on quantum theory).[56]

Birtwistle’s case can help us to understand another fact that is normally forgotten in the histories of “revolutions”. Quantum theory was not, for everyone, that revolutionary, new, theory that was forcing everyone into research. Birtwistle is an example of how one could, in times of change, stick to old methodological—not conceptual—paradigms. And, again, not all the students interested in quantum physics were necessarily potential actors in the

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[52] Nature, “News and Views”, 121, 1928, p. 220.
[53] Birtwistle, G., “The Complementary Nature of the Quantum Theory”, Nature, 122, p. 58.
[54] SHQP, Bohr Collection, n.9.
[55] W. McCrea, “How quantum physics came to Cambridge”, New Scientist, 17, 1985, p. 58. See also, W. McCrea, “Cambridge 1923-6: Undergraduate Mathematics”, in R. Williamson, The Making of Physicists, Bristol, 1987, pp. 53-66.
[56] McCrea in Williamson.

forefront of scientific research. Having both Dirac and Birtwistle teaching advanced courses on quantum mechanics can lead us to think that, as early as the late 1920's, there was room in Cambridge for a two-tier training system in the theory of quanta: one for potential researchers, another for people wanting *only* to be up-to-date with the latest science.

A baker's dozen popular-audience books on quantum physics that I think do a good job presenting the key ideas of the theory and experiments.Â Zeilinger is a major figure in this field-- his name regularly comes up when people try to guess the next Nobel prize in physics-- and this is an excellent treatment. I particularly like the way it walks the reader through looking at "real" data, to see how the spooky correlations of entanglement emerge from measurements of polarized photons. And it would be irresponsible to mention any book by a major figure without also citing Richard Feynman's QED, based on a series of lectures he gave in the early 1980's. This is one of the best explanations you'll find of the idea It covers the experimental basis of quantum physics, introduces wave mechanics, SchrÃ¶dinger's equation in a single dimension, and SchrÃ¶dinger's equation in three dimensions.This presentation of 8.04 by Barton Zwiebach (2016) differs somewhat and complements nicely the presentation of Allan Adams (2013). Adams covers a larger set of ideas; Zwiebach tends to go deeper into a smaller set of ideas, offering a systematic and detailed treatment. Adams begins with the subtleties of superpostion, while Zwiebach discusses the surprises of interaction-free measurements.Â A Mach-Zehnder interferometer, with two beam splitters, two mirrors, and two detectors, is used to test if an Elitzur-Vaidman bomb is functional without detonating it. (Image by MIT OpenCourseWare.)