ANNALS OF SCIENCE, 44 (1987), 617–644

Unfulfilled renown: Thomas Preston (1860–1900) and the Anomalous Zeeman Effect†

D. WEAIRE
Department of Pure and Applied Physics,
Trinity College, Dublin, Ireland

and S. O'CONNOR
Department of Experimental Physics,
University College, Dublin, Ireland

Received 21 May 1987

Summary

When leading spectroscopists in Europe and America were engaged, during 1897, in exploring the recently-discovered Zeeman Effect, they were overtaken by a relatively obscure physicist working in Dublin. Thomas Preston had previously been known only for his excellent textbooks. His achievement in discovering the Anomalous Zeeman Effect was immediately recognized, but his untimely death has deprived posterity until now of a full account of his life and qualities.

Contents

1. Introduction

It is convenient for historians of science that the year 1900 coincides with a critical point in the evolution of physics. Classical physics, the very model of what the scientific method could achieve in understanding and in application, was confronted by a number of puzzling obstacles. In particular, the properties of atoms and the role of the newly discovered electron within them remained inexplicable. One of the many puzzling features exhibited by atomic spectra was the Anomalous Zeeman Effect. This

---

† This paper is based on a contribution to the Symposium on Science and Institutions in Ireland and Britain held in Academy House, Dawson Street, Dublin from 8–12 July 1985, which was arranged jointly by the Royal Irish Academy and the British Society for the History of Science.

is the name given to the Zeeman Effect (splitting of spectral lines in a magnetic field) whenever it departs from the simple triplet form which classical theory predicted. It is in fact the usual form of the effect and, since the advent of quantum mechanics, no longer anomalous.

The discoverer of the Anomalous Zeeman Effect, Thomas Preston, was approaching forty as the century drew to its close. Already his recent discovery and the popularity of his textbooks had won him widespread acclaim—an honorary D.Sc., Fellowship of the Royal Society, and the Boyle Medal of the Royal Dublin Society. He seemed destined to take his place in the first rank of the international physics community in the momentous years to come.

He had for some time, however, been declining in health. On 31 January 1900, his wife Katherine wrote to G. F. Fitzgerald, 'his master and constant friend', to say that he would be unable to accept the Boyle medal in person. He must have been very ill to have been unable to write directly to his great mentor. He died on 7 March 1900. An obituary spoke of 'unfulfilled renown'. Although his name lingers on in textbooks of atomic physics, in association with 'Preston's rule', it is not as renowned as it should be—even in his native Ireland.

We have been successful in locating various items of correspondence and other material with the aid of which certain episodes of Preston's life may be followed. Almost all of this is either in the collection of Fitzgerald's correspondence at the Royal Dublin Society, in the hands of Preston's family, or in one of our two Physics Departments, both of which can lay claim to Preston.

In reviewing Preston's career we shall first give a brief outline and then focus on three aspects. Firstly, his early and mainly mathematical work deserves some mention, and an entertaining dispute with G. J. Stoney is worth recounting. Secondly, we shall comment on his remarkable textbooks. Lastly, his experimental work on the Zeeman Effect must be the climax of our account, as it was of his career.

His work under these three headings—mathematical, pedagogical, experimental—presents a spectrum of achievement of which there can have been few equals, even in that heroic age. After a brief outline of his life and times we shall describe his achievements in each of these categories.

2. Outline of Preston's career

Preston was born on 23 July 1860 at Ballyhagan, Kilmore, County Armagh, and he was educated at Armagh Royal School and Trinity College, Dublin. He entered the College as a pensioner in October 1881. He was an excellent but not totally outstanding student. He graduated in 1885 in Mathematics and Experimental Science.

His arrival at Trinity coincided with the appointment of G. F. Fitzgerald as Professor of Natural and Experimental Philosophy, 'the idol of the undergraduates and the hope of the senior men'. Fitzgerald was determined to give Trinity physics (and Trinity science in general, and Irish science at that) a more practical and experimental flavour. Undoubtedly this was to inspire Preston's eventual drift towards experimental physics. Nevertheless, his early postgraduate work was in the more refined areas of mathematical physics, very much in the established Trinity tradition. More could be gained (possibly a Fellowship) by following this course than by the 'rough-and-ready' methods of Fitzgerald. (the phrase is Stoney's). The MacCullagh Prize examinations were an opportunity to show his mathematical skills, and he was twice successful (1887, 1888), his chosen subjects being 'Attractions and the Figure of the Earth', and 'The Theory of Elasticity'. During this period he also assisted the mathematician, Graves, at

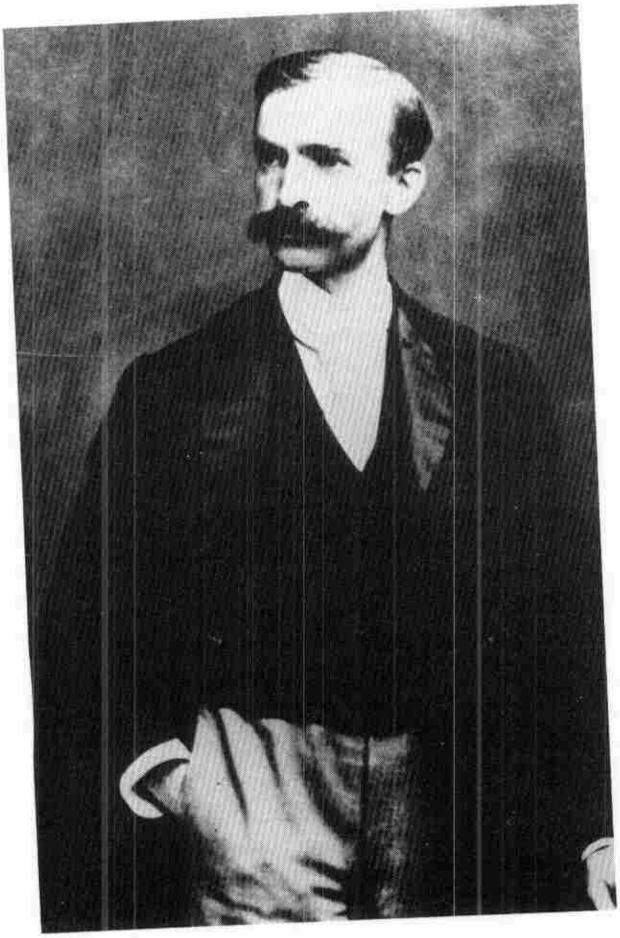


Figure 1. Thomas Preston.

Trinity College, Dublin, did some experimental work in Fitzgerald's laboratory, wrote a couple of minor papers, taught mathematics and mathematical physics at University College, Dublin, and published a textbook, *A Treatise in Spherical Trigonometry* (Macmillan, 1886). His co-author was W. J. McClelland, who was his cousin and a Dublin schoolteacher. The book drew favourable reviews as an 'admirable manual' and an 'excellent treatise, accurate, clearly expressed and clearly arranged'. It ran to several editions. Thus encouraged, Preston embarked on the more substantial and ambitious *Theory of Light*, published by Macmillan in 1890. No Trinity Fellowship was forthcoming, so by 1890 he was looking elsewhere, to the College of Science in Dublin, to McGill University in Montreal, and eventually to University College, Dublin, where he became Professor of Natural Philosophy in 1891.

Much confusion has been engendered by the many changes which took place in Irish Universities at that time, and they are not irrelevant to what follows, so some words of explanation may be excused.

University College, Dublin, was the successor to Cardinal Newman's Catholic University, founded in 1854, which for all its grand ideas was never granted a charter.

Instead, the British Government in 1879 founded the Royal University as a nondenominational body which did not teach but which held examinations for degrees and which maintained fellowships. The Catholic University gradually lost momentum in its uphill struggle without a charter, and in 1883 decided to transfer most of its activities to a College, subsequently known as University College, Dublin, to be run by the Jesuits. In its new form it maintained many of the qualities of the previous institution, typified by the splendid figure of Monsignor Molloy (Preston's predecessor) ex-theologian, collaborator with Marconi, popular public lecturer and unpopular teacher! Although Molloy's magnificent personal collection of demonstration apparatus may induce awe in the beholder today, it should not be inferred that there was adequate institutional support for experimental training and research. When Preston's successor, John McClelland, was visited by old friends from the Cavendish laboratory, they were astonished by the lack of facilities. They were told by the Dean: 'Gentlemen, I am glad to have given you some insight into the conditions under which our Professor of Physics has to work so that when you return to your own university you can say you have learned something new about the Irish University question.'[1]

As already mentioned, the Royal University was purely an examining body which amongst other things gave degrees to University College, Dublin, students. On his appointment to University College, Dublin, Preston became an Examiner at the Royal University and later a Fellow of it. It had excellent laboratories, but as far as students were concerned they could only be used in examinations! There was also some equipment for research. In addition, there was the College of Science, also in Dublin, and this again was comparatively well equipped; Preston was to take advantage of its facilities in due course.

During the decade that he spent at University College, Dublin, Preston wrote another major textbook (*Theory of Heat*, Macmillan, 1894), published a few more mathematical papers, and then embarked on the experimental studies which were to meet with such sudden success. In addition to his academic work he secured a Government appointment as Inspector of Science and Arts from 1894. This brought in a useful income (£460 per annum; more than his university salary) but it must have been an irritating distraction from his real interests, as his letters to Fitzgerald from remote hotels all over Ireland would suggest. Once his reputation was established a move to a major institution seemed likely, but illness and finally his death intervened.

2.1. *Mathematical work*

As we have indicated, Preston's early mathematical work was in the conventional tradition of Trinity at that time, and to the modern reader it has a rather antique quality. Such topics as the 'equilibrium of flexible strings on a spherical surface' are hardly worth close examination here, and we would pass over the subject entirely, were it not for an incident in his later years, which brought him into conflict with George Johnstone Stoney over the proof of a certain theorem. Stoney was a notable adversary. Although then living in London he was the Grand Old Man of Irish physics. He had been one of the first to speculate on the relationship between line spectra and the internal motions of molecules and atoms and was responsible for the term 'electron', which in due course became accepted as the name for J. J. Thomson's 'corpuscles'.

---

[1] *A page of Irish History: Story of University College Dublin 1883–1909* (Dublin and Cork: The Talbot Press Ltd, 1930), p. 207.

In 1896, Stoney sent a series of papers on 'Microscopic Vision' to the *Philosophical Magazine*. Preston chose to question the justification of the very first proposition of that rambling discourse, which was that light could always be analysed in terms of plane waves. This, Preston asserted, was simply a trivial generalization of Fourier's theorem, and Stoney's rather vague and periphrastic arguments could be dispensed with. Unfortunately the latter interpreted this as an attack on his own integrity. Letters flew backwards and forwards between Preston, Stoney, and Fitzgerald, with others such as Rayleigh and Larmor being called upon by Stoney in his own defence. Fitzgerald was caught in the crossfire between a star pupil and an affectionate septuagenarian uncle. He must have felt very uncomfortable.

Eventually Preston published his comments. Stoney replied with further comments at the same time, and then published yet another piece in reply. At this point, Preston himself became irritated. In a second letter to the *Philosophical Magazine* he made his feelings more clear: 'I object to the ease and freedom with which he rides off to infinity on a spherical wave and comes back on a plane wave'.[2] Inevitably, Stoney replied again,[3] in the most extraordinary terms, wandering off into reminiscences of his early Trinity days when he had picked up the lemma in question, just as he had been doing in his correspondence with Fitzgerald. He saw himself as defending the *geometrical* tradition in mathematical physics for which the symbolic manipulations proposed by Preston were no effective substitute. In a footnote he commented that 'another feature which then distinguished the teaching of the University of Dublin in Mathematical Physics was the almost exclusive study of great writers—Newton, Lagrange, Laplace, Poisson, Gauss. MacCullagh, Amperè *etc* instead of recastings of their work by compilers of textbooks'. This was surely aimed at Preston, despite the fact that Stoney himself had heartily congratulated Preston 'on the completion of your great task', when *Theory of Heat* was published.

During the summer of 1897 the dispute gradually cooled off. 'Stoney is coming around' said Preston, the summer had calmed his nerves. So it was, but in any case it is doubtful if Preston would have pursued the matter any further, for he was now engaged in a more important pursuit, as we shall see.

Students of optics or the scientific society of the 1890s may find this little argument and the tangle of letters interesting. For us it demonstrates Preston's fearless and selfless tenacity. Stoney was the very man who had been engaged in furthering his case for election to Fellowship of the Royal Society. This tendency to put a concern for the truth above personal advantage was to show itself again in a later argument with Michelson. As for the substance of the argument with Stoney, neither author really gives a convincingly complete derivation of the proposition, and to that extent one must sympathize with Stoney. Surprisingly, *neither* made any reference to Maxwell's equations, which we might expect to have been the starting point of any satisfactory attack on the problem.

---

[2] Thomas Preston, 'On the General Extension of Fourier's Theorem', *Philosophical Magazine*, 43 (1897), 458–60.

[3] G. Johnstone Stoney, 'On the Proof of a Theorem in Wave-motion', *Philosophical Magazine*, 44 (1897), 98–102.

2.2. *Textbooks*

Preston's two major textbooks were *Theory of Light* and *Theory of Heat*.[4] In addition, he prepared a second edition of *Theory of Light* (1895) with more than one hundred pages added. Despite what Stoney said in the heat of argument, Trinity College had been the source of many important textbooks in physics, going right back to the publication of Richard Helsham's lectures in 1739. Preston was following in an established tradition. He was also taking advantage of the emerging professionalism of physics, which would soon create a substantial demand for books such as his.

The two books are written in a 'magnificent expository style',[5] and are meticulously planned and executed. In the case of *Theory of Heat*, it is further embellished by superb illustrations of apparatus. Sir Arthur Eddington referred to *Theory of Light* as 'the leading textbook of my undergraduate days'.[6] The text has an informed historical perspective throughout, with whole passages quoted from the classic works whenever appropriate—particularly Newton's *Opticks*.

T. H. Savory in his book *The Language of Science* discusses influential textbooks and makes reference to 'that almost unparalleled series of books' produced by Macmillan at the turn of the century.[7] He specifically mentions seven produced between 1890 and 1909; both of Preston's books are included. The young author was justifiably proud of his achievements. He photographed his own bookshelf with the two works rubbing shoulders with some of their great contemporaries—Rayleigh on *Sound*, Thomson and Tait on *Natural Philosophy*. He kept his press cuttings, so one can easily judge the immediate impact of the books. They were widely praised as the clearest guides to their subjects yet produced for the student. Only the *Manchester Guardian* complained of a 'heavy, confused and often inaccurate style'. Nothing could be further from the truth. Perhaps a few words from the Preface to the second book will serve to exemplify the easy rhythm of his writing (as well as his sense of the importance of his work):

> It is but a short time since the pursuit of experimental research was regarded merely as a matter of individual curiosity; but owing to the high commercial value and important bearings of many of the recent discoveries in the fields of science, the public mind has now become awakened to the conviction that knowledge is wealth, and that the scientific education of the people is a matter of national importance.
>
> In the struggle for place it is not surprising that the nobler aspect of science, as an instrument of education and culture, should be lost sight of in the popular desire for a mere acquaintance with the facts demanded by the exigencies of the moment. It cannot, however, be too soon or too often impressed upon the beginner that an acquaintance with a number of facts does not constitute a scientific education, and that there is no royal road to learning other than that by which it is pursued for its own sake.

Many letters of thanks and congratulations also survive, from Thomson (Kelvin), Rayleigh, Fitzgerald, Wiedemann, Quincke, Hertz, Stoney, Ball, Poynting and others.

---

[4] Thomas Preston, *The Theory of Light* (London: Macmillan, 1890). Thomas Preston, *The Theory of Heat* (London: Macmillan, 1894).

[5] I. B. Cohen, in the Preface to the Dover edition of *Opticks* by Sir Isaac Newton (New York, 1952), p. xiv.

[6] A Eddington, *The Philosophy of Physical Science* (Cambridge, 1939).

[7] T. H. Savory, *The Language of Science* (London, 1953), p. 176.

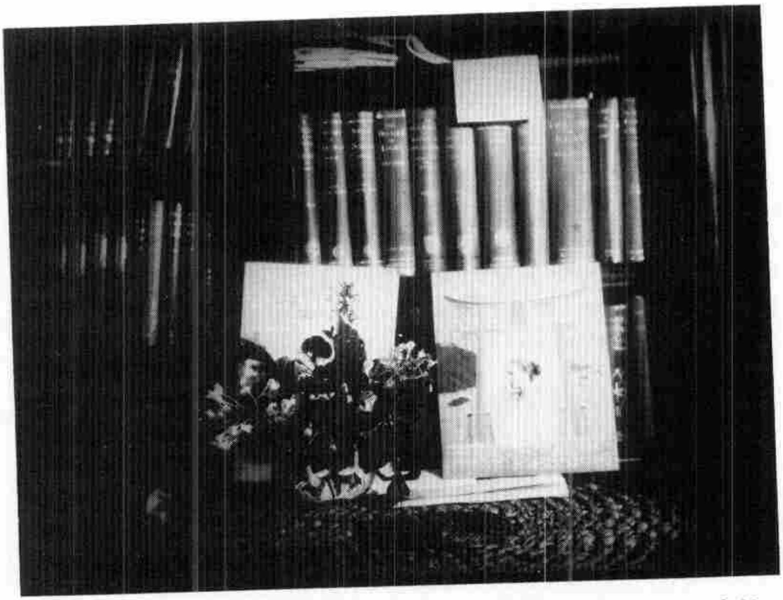


Figure 2. Thomas Preston's bookshelf. In the foreground are a copy of *Nature* and a photograph of his wife.

All were warm in their commendation of the books. Michelson sent a number of corrections for *Theory of Light* and promised to use the second book in his classes. The judgement of later generations was equally favourable, as evidenced by the large number of further editions: *Heat*, second, 1904; third 1919; fourth 1929 (all revised by Cotter); *Light*, third, 1901 (Joly); fourth 1912 (Thrift); fifth 1928 (Porter).[8]

The supreme accolades of science are not reserved for the writers of textbooks, however excellent, but for the finders of new truths. When Preston turned from authorship to experiment, he was quickly to gain that recognition. He had already stated his credo regarding the priorities of physical science in his books, as in the Introduction to *Theory of Heat*:

> Facts are independent of taste and fashion, and are subject to no code of criticism. They are perhaps more useful when they contradict than when they support received doctrines, for our theories at best are only imperfect approximations to the real knowledge of things, and in all physical research doubt is usually an incentive to new labours, and tends continually to the development of truth. The thoughts and questionings of man turn towards the source of natural phenomena and seek a knowledge of the actions which underlie them. By a process of abstraction from experience physical theories are formed which lie outside the pale of experience, but which satisfy the desire of the mind to see every event in nature resting upon a cause. Natural philosophy is an *experimental* and not an *intuitive* science, and *a priori* reasoning cannot alone conduct us to a physical truth. We must endeavour to discover what it is, and not speculate on

---

[8] To infer that Preston's books were in regular use only until the 1930s may be too conservative an estimate. As late as 1954, Preston's *Light* is to be found in a recommended list of texts; see R. H. Whitford, *Physics Texts: A Reference Manual* (Washington, D.C.: Scarecrow Press, 1954).

what it might be, or decide on what ought to have been, and the causes and connections of the phenomena of nature have escaped the apprehension of man for ages by the wilful ignoring of this fact.

2.3. *Atomic spectroscopy*

Preston's family have, by some happy combination of love and neglect, preserved some of his letters and personal effects intact since 1900. One of the present authors, upon asking to see these, was at one point handed the great man's wallet—an unusual privilege for an amateur historian! Along with the usual trivia it contained two small photographs. A spectroscope and a set of spectra—what could be more appropriate, to explain to a stranger what he was doing back in Dublin, while he sat in some country hotel?

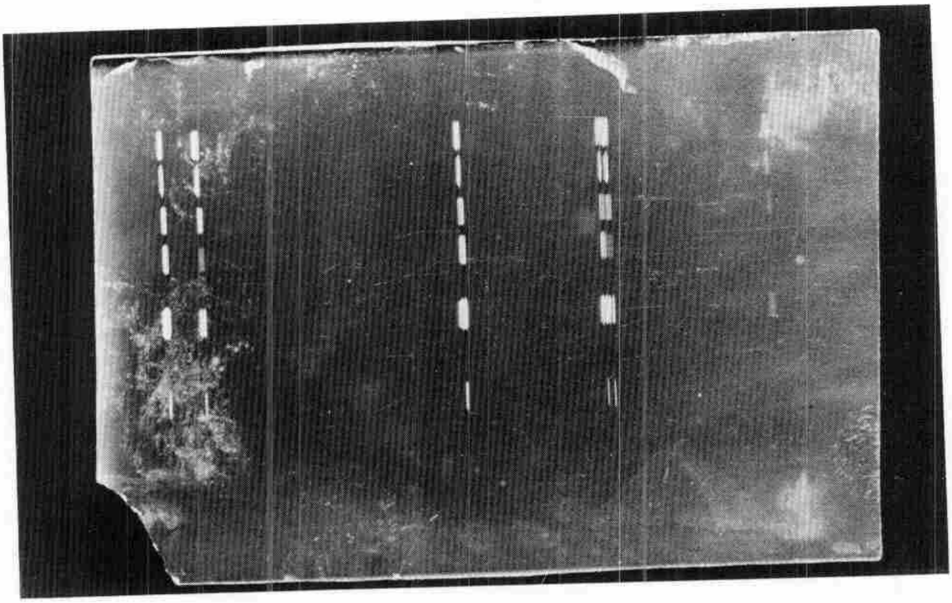
The set of spectra shows an example of the Anomalous Zeeman Effect in cadmium and zinc. In presenting a similar photograph in a talk delivered to the Royal Dublin Society on 22 December, 1897, Preston preempted the work of several leading groups in famous laboratories such as those of Michelson, Cotton, Cornu, and Zeeman himself. How had it come about that the young professor in a poorly endowed institution had startled his contemporaries in this way? It required both the will and the means, so let us take these in turn.

Attempts to determine the effects of a magnetic field on spectral lines had been made many times. An early pioneer in such work was Faraday. However, a sufficient combination of high resolution and high magnetic field was not achieved until 1896. In August of that year Pieter Zeeman, working in the laboratory of Kamerlingh Onnes at Leiden, announced the discovery of such an effect. To be precise, he observed only a broadening, which had (unknown to him) been previously seen by Fievez in 1885. However, he also observed polarization effects which indicated that the line really was split in a manner consistent with the electron theory of Lorentz. Incidentally, Preston himself sided with Fievez in the matter of priority, in a letter to Fitzgerald and in an Appendix to a paper in the *Philosophical Magazine*.[9] He said 'I am strongly of the opinion that M. Fievez was dealing with the real magnetic widening, and that he obtained the effect on a tolerably large scale… No doubt if he had known the theory the whole question would have been settled in 1885'. It was, in Preston's view, the alliance with Lorentz's theory that gave Zeeman's work its decisive impact. The Zeeman splitting gave promise of being a vital clue in the search for an explanation of atomic spectra by classical theory along the lines anticipated by Stoney. Zeeman and Lorentz duly received the Nobel Prize in 1902 for the discovery.

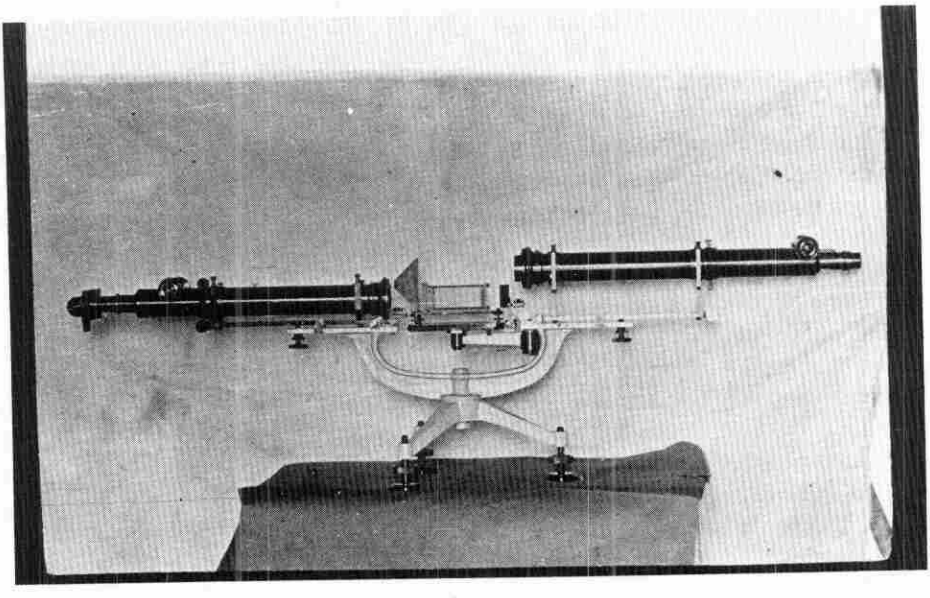
It is probable that Preston first learnt about the Zeeman effect through Fitzgerald. He was one of the community of scientists which orbited around Fitzgerald at Trinity and thus would have early news of all the latest discoveries in Britain and the Continent, together with a forum to debate their implications. However, although Fitzgerald certainly knew about the effect early in February 1897 there is no clear evidence that it came to the forefront of discussions between them until the latter part of 1897. The earliest letter on the topic from Preston which is in the Fitzgerald collection is dated 22 November 1897, and was written some time after he had commenced his own

---

[9] T. Preston, 'Radiation Phenomena in the Magnetic Field', *Philosophical Magazine*, 45 (1898), 325–39.



(*a*)



(*b*)

Figure 3. Photographs found in Preston's wallet. (*a*) shows the Anomalous Zeeman Effect in cadmium and zinc, and (*b*) a spectroscope. This is probably the spectroscope which he had just acquired from Adam Hilger. It incorporates the echelon invented by Michelson. There is no report of Preston using this spectroscope, but he was in debt to Hilger for it at the time of his death.

experimental work.[10] What is striking from that early correspondence in November 1897 and January 1898 is the degree to which the phenomenon of radiation in a magnetic field had become the centre of his attentions and the emphasis which he intended to place on experiment. In that first letter he refers to an earlier discussion with Fitzgerald about Zeeman's ideas and says 'I think indeed that Zeeman's paper is very much to the point and has left little to be said—perhaps something to be done?' On 2 January, 1898, he said 'I am devoting all my time to the experiments at present for I think it best to know all the facts first', thus echoing the passage in *Theory of Heat* which we have quoted above. Clearly Preston was eager to report his progress to Fitzgerald at every stage and Fitzgerald assisted in reporting some of the work in England. As described below, the experimental work drew on the resources of rival institutions: this may account for the rather passive role which the energetic Fitzgerald appears to have played. Indeed, Stoney in a letter to Fitzgerald on 24 January, 1898, laments the fact that the great spectroscope was in the Royal University rather than Trinity, and more or less blames Fitzgerald for letting it happen.

What were the means at Preston's disposal? Cleverly he obtained his initial magnetic field from the College of Science and his high resolution from the Royal University. Preston was particularly fortunate in being offered laboratory facilities at the Royal University, where the Curator and Examiner in Chemistry was Dr W. E. Adeney, later to become acting Professor of Chemistry at the College of Science. Amongst other activities Adeney served on Royal Commissions on whiskey and sewage disposal!

A short time previously Adeney had supervised the installation of a large Rowland spectrometer at the Royal University. The supplier of the grating, which had a focal length of 21·5-feet and a ruled width of 6-inches with 14438 lines per inch, said in a letter: 'Professor Rowland states all lines are clear and sharp', and added 'You are very fortunate in getting this grating for no one knows when we will get another'. It is a tribute to the generosity of Adeney and the local appreciation of Preston's work that he was given access to this large instrument so soon after its installation—indeed even before a description of the mounting itself was given to the Royal Dublin Society on 16 February, 1898.[11]

The first electro-magnet which he employed was lent to him by Professor Barrett of the College of Science. It was of the 'usual U-shaped type, of moderate power and had a core of about 2″ diameter of soft iron'. Using this magnet he succeeded in 'photographing all the (visual) appearances described by Zeeman', and on 19 November, 1897, he sent a letter to *Nature* together with three small negatives. The letter was published on 23 December, 1897, with a note by the editor saying 'the negatives referred to by Mr. Preston show clearly the effects described, but they do not lend themselves to satisfactory reproduction even when enlarged'.[12]

Although still debating the theoretical issues with Fitzgerald, Preston had now become more interested in 'working up his magnetic field' and pressing ahead with

---

[10] The letters from Preston to Fitzgerald which we refer to throughout the paper are all in the Fitzgerald Collection at the Royal Dublin Society. There are five letters from the year 1897 dated 12 and 16 February, 7 July, and 22 and 24 November. The first three make no mention of the Zeeman Effect, while the latter two are totally concerned with it. It should be noted that two letters written on 9 and 13 January 1898 were inadvertently dated 1897 by Preston. We are grateful to Professor Bruce Hunt for drawing our attention to this point.

[11] W. E. Adeney and James Carson, 'On the Mounting of the Large Rowland Spectrometer in the Royal University of Ireland', *Scientific Proceedings, Royal Dublin Society*, 8 (1898), 711–16.

[12] T. Preston, 'The Zeeman Effect Photographed', *Nature*, 57 (1897), 173.

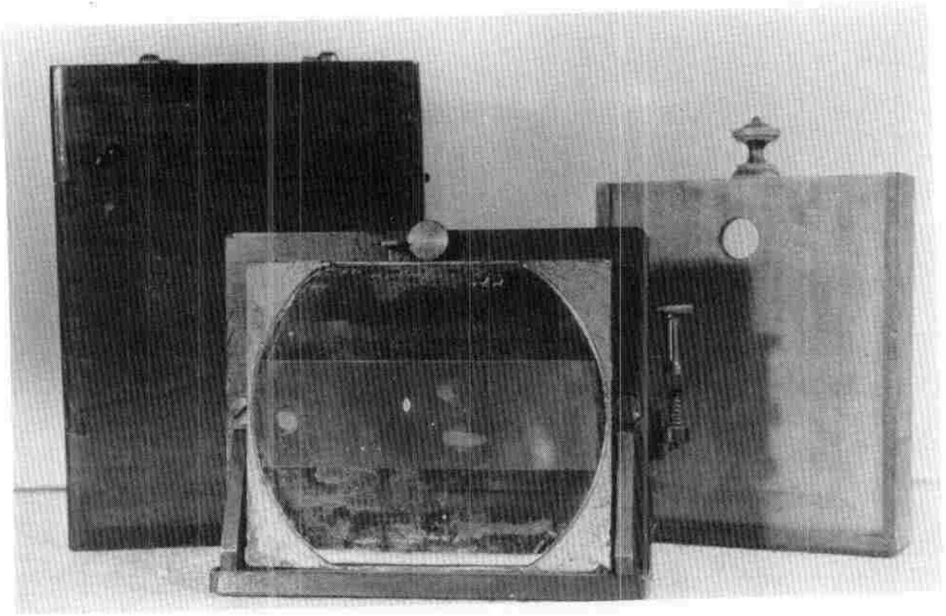


Figure 4. The Rowland grating used by Preston. It has a 21-foot radius of curvature and is currently in the Physics Department at University College, Dublin.

experiments. He had noticed early in his experimental work that the Zeeman splitting did not in general follow the simple form predicted by classical theory, and he realized that if he was to investigate this properly he would require a stronger magnetic field. Towards this end he decided to have a magnet constructed to his own special design by the Dublin instrument makers Yeates and Co. While waiting for this magnet (with which he subsequently obtained fields of up to 50 000 c.g.s. units) he was fortunate to be able to borrow a large U-shaped magnet from Monsignor Molloy with which he obtained field strengths of about 25 000 c.g.s. units, and with which he made rapid and considerable progress in his investigations.

Thus it was that in December 1897, in a paper read to the Royal Dublin Society, Preston presented experimental results, including photographs suitable for reproduction, which in a number of cases were clearly at variance with the 'normal' triplet nature of the line splitting reported by Zeeman and predicted by the Lorentz theory for observations perpendicular to the lines of magnetic force.[13] 'It is clear', he said, 'that the magnetic effect depends not so much on the wave-length of the spectral line as on some hidden quality which we may refer to as the character of the line; for lines of nearly the same wave-length, even of the same substance, show effects which differ remarkably in magnitude and character. Such laws, therefore, as that the broadening of the spectral lines is proportional to the wavelength or to the square of the wavelength are shown to be utterly untenable, unless perhaps it might be possible to group the spectral lines of each substance into sets, so that some law of wavelength might apply to the lines of each set.'

---

[13] T. Preston, 'Radiation Phenomena in a Strong Magnetic Field', *Transactions Royal Dublin Society*, 6 (1898), 385–91.

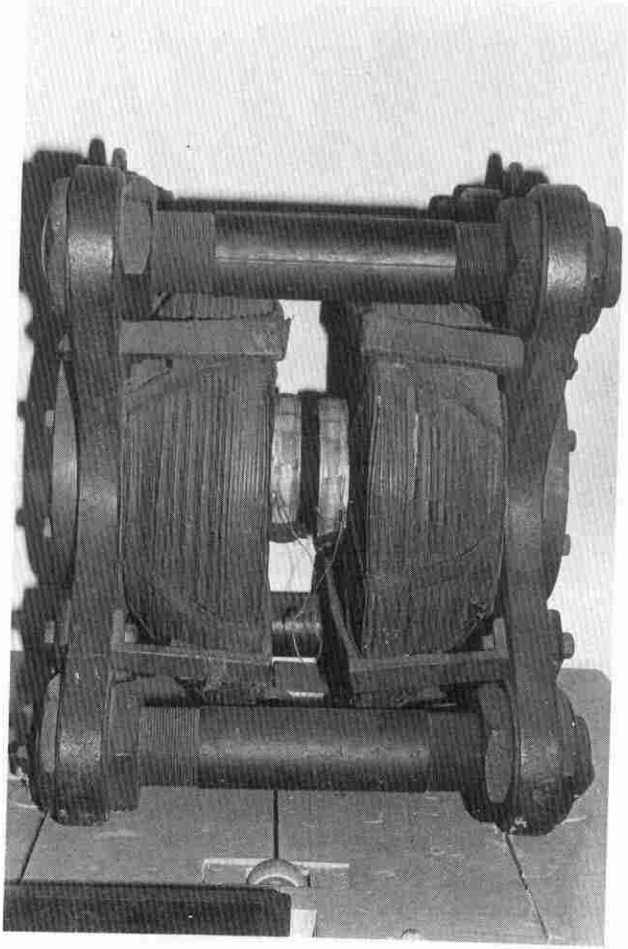


Figure 5. The magnet constructed to Preston's special design by Yeates and Company. It is 25 inches high.

To discuss Preston's work further in a meaningful way it will be necessary to set it in the context of other work at the time, particularly that of Zeeman himself. At this point readers unfamiliar with the classical and quantum theories of the Zeeman Effect may wish to consult the Appendix.

3. Zeeman Effect: experimental background

Zeeman in his first paper—of which there are translations in English in the *Philosophical Magazine* and the *Astrophysical Journal*,[14] as well as the communications of the Leiden laboratory—concentrated particularly on the sodium *D* line doublet. From visual observation using the first order of a Rowland grating with a radius of 10 feet and 14 438 lines per inch, he suggested that in a field of 10^4 c.g.s. units the

---

[14] P. Zeeman, 'On the Influence of Magnetism on the Nature of the Light Emitted by a Substance', *Philosophical Magazine*, 43 (1897) 226–39, and *Astrophysical Journal*, 5 (1897), 332–47.

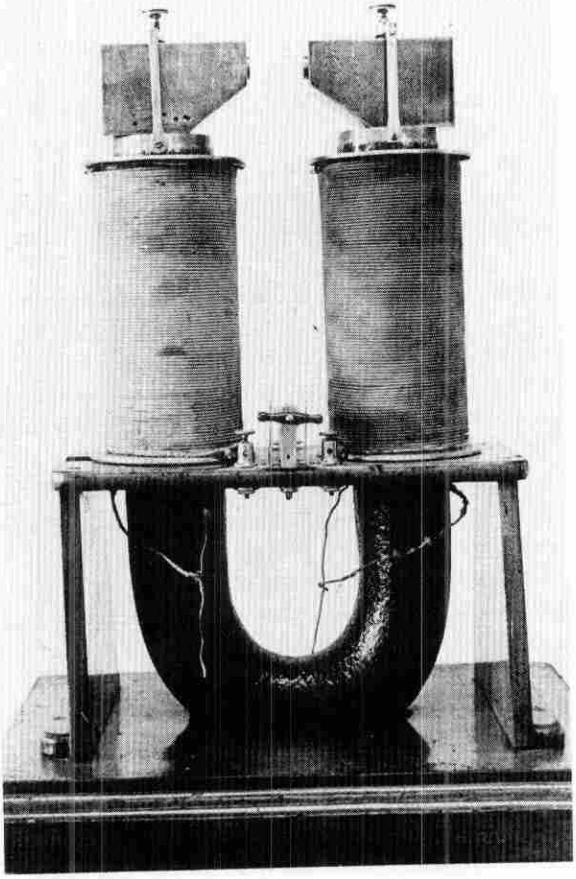


Figure 6. The magnet which Preston borrowed from Monsignor Molloy.

lines were widened on both sides by about 1/40 of the distance between the *D* lines. He did not distinguish between the broadening of the two lines, and the only reference to line structure was through polarization effects. He reported that the outer edges of the lines were circularly polarized in opposite directions for longitudinal observation and plane polarized in transverse observation. The polarization tests were made in response to a suggestion by Lorentz and the results were found to be consistent with his theory. In a subsequent paper entitled 'Doublets and Triplets in the Spectrum produced by External Magnetic Forces', published by Zeeman in Dutch and English (July and September 1897) the whole emphasis was on observing the doublet and triplet structure predicted by Lorentz.[15] Zeeman had up to then concentrated mainly on sodium. He

---

[15] P. Zeeman, 'Doublets and Triplets in the Spectrum produced by External Magnetic Forces', *Philosophical Magazine*, 44 (1897), 55–60 and 255–59.

now reported that he did not succeed completely with the means at his disposal in observing the expected doublets and triplets until he eventually tried the blue (4800 Å) line of cadmium. For this line he said: 'Now I succeeded, indeed, in observing the expected phenomena (doublet and triplet)' Initially the triplet nature of the structure was inferred from polarization effects but with a field of 32 000 c.g.s. units he reported a tripling of the line without using any nicol prism. We now know that the full structure is a six-fold splitting which may appear as a quartet with lesser resolution or as an unresolved triplet if one makes use of a nicol prism. Given that Zeeman (by then in Amsterdam) was making his difficult observations with an eyepiece using a small grating of 6-foot radius, it must be concluded that in this case he tended to see what he expected to see.

It was a difficult time for Zeeman from the experimental point of view. He had been appointed a lecturer in Amsterdam in January 1897, and the disruption to his work caused by the move from Leiden was exacerbated by inferior facilities. In his doublets and triplets paper he remarked, 'I missed, however, the beautiful Rowland grating I used in the laboratory of Professor Onnes. I now only had at my disposal a smaller one with a radius of 6′ but like the Leyden one with 14,438 lines to the inch'. Further, as Zeeman says in his book, the mounting arrangement was unsatisfactory.[16] Grating, slit and photographic camera were mounted on a large wooden table in one of the upper rooms of the laboratory, which were the only rooms at his disposal. The table rested on a wooden floor and the small vibrations caused by people on the upper floor of the laboratory and even by outside traffic from the adjacent streets meant that only one out of about thirty photographs was useable. Consequently, Zeeman abandoned comprehensive photographic work requiring high stability until about 1907, by which time he had a rigid mounting of a 4-inch grating. He did, however, submit a report on his early photographic work to the *Philosophical Magazine* on 31 December, 1897, in which he still concentrated on triplet structure saying 'For purposes of measurement there are several advantages in photographing the outer components of the magnetic triplets, quenching the light of the middle line by means of a nicol'.[17]

Over the next three or four years Zeeman published relatively little, and his disappointment in not being the first to report the Anomalous Effect is evident from his book. Saying that he himself had in 1897 noticed peculiarities in the resolution of zinc and cadmium lines, he continued: 'Before I had completed and fully discussed my observations, publications appeared by Preston, Cornu, and Michelson, all of them almost simultaneously, on the same phonomenon'.[18] Elsewhere referring to the same period of his work he said: 'In the course of this part of the investigation it appeared that other observers were in the field, who worked in more favourable circumstances'.[19]

In his book, Zeeman is careful to give Preston marginal priority over Cornu and Michelson in reporting the Anomalous Zeeman Effect.[20] Otherwise he comments little on their reports. We will, therefore, say something about the work of Cornu and Michelson in this area before returning to Preston. Cornu published only two papers

---

[16] P. Zeeman, *Researches in Magneto-Optics*, (London, 1913), pp. 56–57.

[17] P. Zeeman, 'Measurements Concerning Radiation—Phenomena in the Magnetic Field', *Philosophical Magazine*, 45 (1898), 197–201.

[18] Zeeman (footnote 16), p. 58.

[19] Zeeman (footnote 16), p. 57.

[20] Zeeman (footnote 16), p. 60.

on the Zeeman Effect.[21] In the first in October 1897 he confirmed the doublet and triplet splitting reported by Zeeman for the sodium D lines. He used a 10-foot concave grating and an ocular as the detector. By cleverly incorporating a doubly-refracting prism into his optical arrangement he was able to separate his image into adjacent parts according to its state of polarization. Over the next few months Cornu improved his optical system largely through the use of a spectroscope using a plane diffraction grating in the third order. In January 1898, in a short paper, he presented new results which he said were not in agreement with earlier observations, and in two highlighted summaries he said:

> The effect of the magnetic field on the period of vibration of the radiations of a luminous source seems to depend not only upon the chemical nature of the source, but also upon the nature of the group of spectral lines to which each radiation belongs, and on the part which it plays in the group.

and

> Under the influence of the magnetic field in the direction normal to the lines of force a single spectral line becomes QUADRUPLE (and not TRIPLE, as has been previously announced). The two outer lines are polarized parallel to the line of force, the two intermediate lines perpendicular to this direction.

The first quotation suggests a train of thought similar to that which Preston had in working towards the results which became known as Preston's Rule. The second was a premature generalization of his observations particularly as one of his diagrams suggests that he was on the verge of seeing the six-fold splitting of the D_2 line of sodium. Apart from a note a week later providing data inadvertently omitted from his second paper, Cornu does not appear to have contributed further to the study of the Zeeman Effect.

Michelson's first paper on the Zeeman Effect was published in July 1897.[22] He described his use of the interferometer to examine the magnetic broadening of spectrum lines which had a short time earlier been reported by Zeeman. He suggested that for small effects the interferometer should have an advantage over a good spectroscope. By interpreting visibility curves he concluded that lines of sodium and cadmium *were doubled for both transverse and longitudinal observation* with a broadening of the components in the transverse case but not in the longitudinal case. Zeeman, at the end of his paper on doublets and triplets, comments on the discrepancy between his transverse observations and those of Michelson and offers an explanation. Zeeman suggested that the two states of polarization within the magnetic triplet would reflect differently at the inclined beam splitter and compensating plate within the interferometer thus possibly weakening the central component to a considerable degree. Zeeman concluded by inviting Michelson to give his opinion. In a note subsequently added to the end of his paper Zeeman said that Michelson had just informed him that he believed Zeeman's explanation of the discrepancy to be correct.[23]

---

[21] M. A. Cornu, 'On the Observation and Kinematic Interpretation of the Phenomena Discovered by Dr. Zeeman', *Astrophysical Journal*, 6 (1897) 378–83, and 'On Certain New Results Relating to the Phenomena discovered by Dr. Zeeman', *Astrophysical Journal*, 7 (1898), 163–69. The two papers mentioned were first published in French in *Comptes Rendus* in October 1897 and January 1898.

[22] A. A. Michelson, 'Radiation in a Magnetic Field', *Philosophical Magazine*, 44 (1897), 109–15, and *Astrophysical Journal*, 6 (1897), 48–54.

[23] Zeeman (footnote 15), p. 259.

Michelson does not appear to have publicly acknowledged his initial error in any of his own subsequent publications, nor does he appear to have tempered his interpretation of visibility curves with words of caution. This characteristic is interesting in view of his subsequent disagreement with Preston.

In his second paper submitted to the *Astrophysical Journal* in January, and published in February 1898, Michelson, without any reference whatsoever to his first paper, starts off by saying that 'further analysis of the radiations emitted in a magnetic field shows that the phenomenon is much more complex than was supposed', and 'an examination of the separate components of the "triplet" brings out the fact that in general these are multiple lines'.[24] He then presented eight laws based on his observations. These were quite specific in form although qualified to some extent in the text. In particular it was the second of these laws which gave rise to Preston's dispute with him. The law stated 'The separation is proportional to the strength of field and is approximately the same for all colors and for all substances.' This was clearly at variance with Preston's description of his own work to the Royal Dublin Society in December 1897, and to the Royal Society in January 1898. In the latter paper, after discussing the varied splittings which he had observed and his hopes for future work, Preston had said: 'In the meantime it may be taken as thoroughly determined that it is untrue to assume that there is any such law as that the effect is uniform for the various spectral lines of any substance, or that the effect varies as the wavelength or as the square of the wavelength'.[25] We will return to the dispute itself later.

Michelson also gave intensity profiles of the spectral splitting. These profiles consisted mainly of genuine features, but they also contained artifacts. Nowhere in the text does Michelson indicate which of the weaker features he regarded as genuine and which if any he regarded as spurious. The paper is surprisingly ambiguous in its presentation. For example, he gives a measurement and category for the sodium yellow lines but does not distinguish between the two lines. Again he gives a measurement and category for the 'blue' line of zinc when in fact there are three related blue lines each different in its Zeeman structure.

Michelson's next relevant publications were a note and paper published in March and June 1898 about his new echelon spectroscope.[26] After describing the new instrument he explained that he had undertaken an extended investigation of the Zeeman effect in order to test the practical efficiency of the instrument. The observations he said 'completely confirm the experiments made by the method of visibility curves'. This was undoubtedly true in a general way, but in fact there was a lack of precision in the presentation of data in this paper as in the previous one. Perhaps Michelson was more interested in the performance of instruments of his own creation than he was in the Zeeman phenomenon. Apart from a reply to Preston's criticism which he published in March 1899, Michelson did not publish further on the Zeeman effect.[27]

Other eminent workers such as Cotton and Becquerel were also active in the field and published profusely but their efforts were primarily directed towards polarization effects rather than the line splittings which had become the focus of Preston's attention.

---

[24] A. A. Michelson, 'Radiation in a Magnetic Field', *Astrophysical Journal*, 7 (1898), 131–38.

[25] T. Preston, 'On the Modifications of the Spectra of Iron and Other Substances Radiating in a Strong Magnetic Field', *Proceedings Royal Society*, 63 (1898), 26–31.

[26] A. A. Michelson, 'The Echelon Spectroscope', *Astrophysical Journal*, 8 (1898), 37–47.

[27] A. A. Michelson, 'Radiation in a Magnetic Field', *Nature*, 59 (1899), 440–41.

4. Preston's contribution

Let us now return to Preston's own work on the magnetic splitting of spectral lines. In his paper read to the Royal Dublin Society in December 1897, he had presented photographs of spectra showing the magnetic splittings of a number of lines in cadmium and zinc. He also reported that he had observed four-fold and six-fold splitting for the sodium D_1 and D_2 lines respectively. His photographs were of a high quality and the clarity of them must have had a profound impact. The advantages of using photographs instead of visual observation (as used initially by most of his contemporaries) are well described in Preston's own words taken from his paper read to the Royal Society in London on 20 January, 1898.[28]

> I naturally decided to study the phenomena by means of photography as well as by eye observation, for the latter, besides being applicable in the visible portion of the spectrum alone, lends itself somewhat to the personal bias of the observer in the case of small and doubtful effects. The photographic plate, on the other hand, gives a faithful record of the phenomena as they actually exist in the image focussed upon it, and this record can be examined at leisure. Moreover, as a considerable length of the spectrum can be photographed at a single exposure, the effects produced on many lines, under exactly the same circumstances, can be compared with precision.

Preston stated quite clearly from an early stage that the magnitude of the magnetic splittings did not follow any simple law. He also classified in clear terms the types of splitting which he had observed, and in his *Philosophical Magazine* paper of April 1898 he provided illustrations to accompany verbal descriptions such as 'normal triplet, weak middled quartet, doublet, double doublet and sextet'.[29] At this stage Preston still inclined to the view that the complexity of the structures, as distinct from their magnitudes, could be explained as modifications of the normal triplet caused by reversal, i.e. more or less complete absorption in one or more of the constituents of the triplet. To be sure he had always maintained that the appearance of the modifications was not that which was usually associated with reversal and in the early stages of his work, he had endeavoured to clarify the matter by variations of exposure times and vapour densities, but without conclusive results. He realized that if he was to push the reversal theory to a definite conclusion he would need a more powerful electromagnet.

The more powerful magnet was also needed if he was to pursue his declared aim of seeking a law governing the magnetic splittings. His work was interrupted while he waited for the new magnet, and apart from a report to the British Association for the Advancement of Science in September 1898 he did not publish after April 1898 until January 1899. In his paper of 18 January, 1899, to the Royal Dublin Society, Preston talks of resuming work with 'improved apparatus' when referring to the new magnet which he said 'has in every way acted up to expectation'.[30]

---

[28] Preston (footnote 25), p. 26.

[29] T. Preston, 'Radiation Phenomena in the Magnetic Field', *Philosophical Magazine*, 45 (1898), 325–39.

[30] T. Preston, 'Radiation Phenomena in a Strong Magnetic Field, Part II—Magnetic Perturbations of the Spectral Lines', *Transactions Royal Dublin Society*, 7 (1899), 7–22.

The first six months of 1899 were to see a spate of papers by Preston.[31] He confirmed that the reversal hypothesis was untenable and that the observed structural complexities were genuine magnetic splittings, he queried aspects of Michelson's work and he provided the results which formed the basis of what is now known as Preston's Rule. This rule says that all the lines of a spectral series have exactly the same pattern. It was already well known amongst spectroscopists at that time that the spectral lines of many elements could be grouped into series so that the frequencies of the lines varied smoothly with a running number. Preston suggested that the Zeeman pattern was the same in all respects for all the corresponding lines of a given series, and that this similarity carried over from one element to another where such elements had similar types of series. An example which he used to illustrate this result was the triplet series in the chemically similar elements cadmium, zinc and magnesium. In terms of current notation he showed that all the ${}^3S_1{-}{}^3P_0$ lines had a simple triplet Zeeman pattern and he applied the theory of Lorentz and Larmor to express the magnitude of the splitting in terms of a particular value of e/m. In a similar fashion he showed that all the lines which we now know as ${}^3S_1 - {}^3P_1$ transitions had a sextet Zeeman pattern whereas the ${}^3S_1{-}{}^3P_2$ lines had a nonet pattern each group having its own value for e/m. It is perhaps idle to speculate as to where these findings would ultimately have led Preston had not his premature death intervened. However, his line of thought may be gauged by an extract from his paper to the Royal Institution in May 1899. In the course of discussing his findings he said:

> In other words, we are led to suspect that not only is the atom a complex composed of an association of different ions, but that the atoms of these substances which lie in the same chemical group are perhaps built up from the same kind of ions, or at least from ions which possess the same e/m, and that the differences which exist in the materials thus constituted arises more from the manner of association of the ions in the atom than from differences in the fundamental character of the ions which build up the atoms; or it may be, indeed, that all the ions are fundamentally the same, and that differences in the value of e/m or in the character of the radiations emitted by them, or in the spectral lines produced by them, may really arise from the manner in which they are associated together in building up the atom.

Such ideas are consistent with the concept of atomic orbitals and the coupling schemes with which we are familiar today although considerable jumps have to be made to overcome the gap between them.

We will now return to the dispute between Michelson and Preston which was mentioned briefly in the earlier discussion of Michelson's work. As in most cases of

---

[31] Ibid., T. Preston, 'Radiation Phenomena in the Magnetic Field', *Nature* (1899), 224–29; idem, 'General Law of the Phenomena of Magnetic Perturbations of Spectral Lines', *Nature*, 59 (1899), 248; G. J. Stoney and T. Preston, 'Illusory Resolutions of the lines of a Spectrum, *Nature*, 59 (1899), 294 (Preston's contribution here was just a brief comment on a note by Stoney which attempted to explain how apparent resolutions of spectrum lines could be illusory: the stimulus for Stoney's note was the earlier critical comment by Preston on some of Michelson's interferometric results); T. Preston, 'Magnetic Perturbations of the Spectral Lines—Further Resolutions of the Quartet', *Nature*, 59 (1899), 367; idem, 'Radiation Phenomena in the Magnetic Field—Magnetic Perturbations of the Spectrum Lines', *Philosophical Magazine*, 47 (1899), 165–78; idem, 'Radiation in a Magnetic Field', *Nature*, 59 (1899), 485; idem, 'The Interferometer', *Nature*, 59 (1899), 605; idem, 'Magnetic Perturbations of the Spectral Lines', *Nature*, 60 (1899), 175–80. This is a reprint of Preston's lecture to the Royal Institution on 12 May, 1899. It was also published in *Proceedings of the Royal Institution*, 16 (1899), 151–63.

dispute there is a certain confusion between matters of substance and matters of style. The particular problem for Preston was the tendency of Michelson to over-generalize when reporting his Zeeman work, particularly in stating it as a law that the magnetic separation was approximately the same for all colours and substances. This ran counter to the thrust of Preston's published reports, and it drew strong and immediate reaction from him in his private correspondence to Fitzgerald. In his letter of 15 March, 1898, to Fitzgerald he refers to Michelson's paper and says: 'It is simply preposterous nonsense to say that the effect is the same for all wavelengths and all substances—that really is going *too* far! After that I am not surprised at anything the Refractometer and his integrating machine may disgorge!' The more restrained public criticism which initiated the dispute was contained in a paper to *Nature* in January 1899. In it Preston remarked 'That the interferometer has led to such a law as that announced by Prof. Michelson shows that there is some peculiarity of the instrument not yet taken into account'. He also mentioned that the complex structure of spectral lines reported by Michelson years earlier in 1892 had never been observed by means of an ordinary form of spectroscope. These remarks must have struck hard at the justifiable pride which Michelson had in his high-resolution work with the interferometer, particularly as they followed so soon after Michelson's earlier error in reporting magnetic doubling of all spectral lines. Michelson replied to Preston in a paper in the issue of *Nature* for 9 March, 1899, saying that spectroscopes did not have the resolving power necessary to confirm his earlier high-resolution work and emphasizing that he had used the word 'approximately' in formulating his law for the magnitude of the magnetic splittings. Michelson again presented data from his earlier papers in support of this 'approximate' law.

It might be noted here that Preston and most other spectroscopists had never used an interferometer. Indeed, Zeeman in his book published in 1913 pointed out that the Michelson interferometer had practically unlimited resolving power. He added: 'But this method, which has been applied by Michelson to investigations on the structure of spectrum lines since 1892, requires such a high degree of personal skill that it has scarcely been used outside the Chicago laboratory'.[32]

Preston responded to Michelson's paper in a letter to the editor of *Nature* which was published two weeks later. He began on a conciliatory note by saying that there were important questions to be asked about the interferometer as a fully reliable instrument and while it had been suggested that structures indicated by the interferometer were entirely instrumental, that he, Preston, was personally of the opinion that the complex structures (in the absence of magnetic fields) earlier reported by Michelson were *in the main* real. He went on to say that this result had added one more to the long list of achievements in the advancement of Science for which they were indebted to Professor Michelson. The plaudits ended there as Preston launched into a renewed criticism of the law put forward by Michelson, saying that 'the facts of the case are that no such law holds, even as the roughest approximation'. Preston supported his case by specifically querying several of the results which had been presented and represented by Michelson.

The controversy stimulated Lord Rayleigh to make a few remarks in a letter to the editor of *Nature*, but in essence he said that Preston's criticism was something which only Michelson himself could answer.[33] The resolution of the conflict seems to have

---

[32] Zeeman (footnote 16), pp. 21–22.

[33] Lord Rayleigh, 'The Interferometer', *Nature*, 59 (1889), 533.

come about in a private manner similar to that of the earlier contretemps between Michelson and Zeeman. In the course of a letter on the interferometer to the editor of *Nature* in April 1899, Preston said: 'I am very glad, however, to hear from Prof. Michelson that the law announced by him was probably generalized from insufficient data, and that the interferometer is not at fault. This being conceded, and the law abandoned, I am thoroughly satisfied, and my confidence in the instrument is re-established.'[34] Michelson himself never again published on the Zeeman Effect.

We conclude this section on Preston's work as an original scientific investigator with a quotation which should still be an inspiration to any aspiring scientist today. It is taken from his lecture to the Royal Institution. He said:

> even though it may be that a knowledge of the ultimate constitution of matter must for ever remain a sealed book to our enquiries, yet, framed as we are, we must for ever prosecute the extension of our knowledge in every direction; and in pursuing knowledge it frequently happens that vast acquisitions are made through channels which at first seem most unlikely to lead us any further. It has frequently happened that small and obscure effects, obtained after much labour and difficulty, have led to results of the highest importance, while very pronounced and striking effects which have forced themselves on the attention of the observer have proved comparatively barren.

At the time of his lecture Preston was already suffering from the gastric ailment which was to lead to his death. This may have been responsible for the rather poignant manner in which he reviewed his achievements and his hopes for the future. Those hopes were next expressed in a letter to Fitzgerald, from what was to prove to be his deathbed, when he said 'I have planned out a lot of scientific work for the future which will give me tremendous pleasure if I can only get health and time to do it'.

4.1. *Later developments*

The establishment of Preston's rule helped the Zeeman Effect to become a powerful tool in spectrum analysis. Further study and development of the rule was undertaken by Runge and Paschen in Hanover in 1900.[35] Shortly afterwards Paschen moved to Tubingen, but Runge continued to make quantitative measurements, and over the next few years came to the conclusion that all known Zeeman splittings could be expressed as rational multiples of the 'normal' triplet splitting. This result became known as Runge's Rule.

Paschen and his students continued to work on the Zeeman Effect. The doctoral thesis of the student Ernst Back, 'Zur Prestonschen Regel', was accepted in 1913.[36] The thesis contained a study of apparent exceptions to Preston's Rule and led to the formulation of what is now known as the Paschen–Back Effect. This is the name given to the phenomenon observed with strong magnetic fields in which the Anomalous Zeeman Effect changes over to the normal effect with increasing magnetic field strength. It occurs when the magnetic splitting becomes greater than the LS multiplet splitting of the field-free atom. Since the latter splitting varies from one atom to another

---

[34] Preston, 'The Interferometer' (footnote 31).

[35] P. Forman, articles on Back, Paschen, and Runge in *Dictionary of Scientific Biography*, edited by C. C. Gillispie, 16 vols (New York, 1970–80).

[36] Idem, article on Back.

and from one term to another for a given atom the question of whether a magnetic field is weak or strong is a relative one. In the case of the lines closely studied by Preston any practical magnetic field (even up to 50 000 c.g.s. units) would be considered weak.

The explanation of the Anomalous Zeeman Effect and the theoretical basis for Preston's Rule did not emerge until the mid-1920s with the introduction of the concept of electron spin and the development of wave mechanics.

5. Conclusion

There is little doubt that Preston achieved a considerable reputation within the British Isles. This is evident from the many honours which came his way in his final years and from a reading of obituaries and other contemporary comments about him. When the British Association for the Advancement of Science set up a committee to report on 'Radiation from a Source of Light in a Magnetic Field' it selected Fitzgerald and Preston as Chairman and Secretary respectively, with such eminent names as Schuster and Lodge amongst the committee members. The committee was given two grants of £50 and £25 to prepare its report, and it is clear that the three reports which were made centre almost entirely on the work of Preston. The first in 1899 includes a detailed outline of Preston's Rule as well as other work by Preston. The second in 1900 regretfully reports a total lack of progress due to Preston's illness and death, while the third in 1901 reports the result of examining negatives left by Preston. Obviously nobody else within the British domain was seriously engaged in work on the Zeeman Effect.

Preston's work was less well known on the Continent and sadly his last paper (*Nature*, November 1899) concentrates on trying to establish his priority in observing the Anomalous Zeeman Effect, including the quartet form. He pointed out that at that time it seemed to be generally accepted that the quartet form had first been observed by Cornu whereas he had reported it in December 1897 and Cornu had not reported it until 1898. This he attributed to the fact that Cornu had published in the widely read weekly journal *Comptes Rendus*, whereas his results had first appeared in the Transactions of a local learned society. These were slow in appearing and little read or known outside their immediate place of publication, despite the excellence of the Royal Dublin Society's publications of that period.

What of the man himself? A capacity for sheer hard work seems to have been a prime characteristic of Preston. During his last years he was travelling widely as Inspector of Science and Arts, teaching at University College, Dublin (where he was a popular lecturer), conducting his pioneering research on the Zeeman Effect, and apparently starting another textbook, all at the same time. He remained a young man in a hurry until the end, and perhaps this accounts for his perforated duodenal ulcer. His letters to Fitzgerald deviate very little from single-minded pre-occupation with the latest theoretical or experimental problem of mutual interest. The only exceptions were occasioned by the birth of babies in one family or the other, and even these are jokingly described in physical terminology ('another atom', 'vortex-tangle-baby' etc.).

We cannot know how he would have adjusted to the great changes in physics that were to come. It may be that he would have dreamed Night Thoughts of a Classical Physicist, for that he certainly was—he did not seem particularly aware of the developing crisis in physics. His own discovery of the Anomalous Zeeman Effect was one of the nails in the coffin of classical physics, yet he talked to the end of 'vibrating ions' in the expectation of a simple classical explanation.

But this is probably an unfair use of hindsight. He was in many respects a modern physicist—serious and professional in everything that he did, industrious and tenacious in a century which had sometimes seen the dilettante admired as a model. Even the great Fitzgerald could be accused of that fault. For all Fitzgerald's personal qualities, his vision of the role of science and his wide influence, most of his actual published material lacks substance. The contrast between the two men is great, but should not be overemphasized, because Preston was, after all, the product of Fitzgerald's teaching, as he acknowledged, His love of physics, his respect for the role of experiment, perhaps even his elegant prose style: these were the gifts of Fitzgerald.

Preston died in considerable debt to the instrument makers Yeates and Hilger. Although he had received grants totalling about £200 toward his research he had personally expended a similar amount of his own money on his work. A final measure of the considerable esteem in which the academic world held Preston and his work may be gleaned from an examination of the large list of subscribers to the Preston Memorial Fund, and from the prestigious list who petitioned the First Lord of the Treasury on behalf of his widow and two young children aged about three and four years. The list included Blythswood, Kelvin, Rayleigh, Larmor, Lodge and J. J. Thomson.

5.1. *Epilogue*

Preston's obituary was published in the *Physical Review* together with his portrait.[37] His predecessors were Bunsen and Wiedemann. The next face to stare from the pages of that journal was that of George Francis Fitzgerald, who followed his pupil in 1901.[38]

Acknowledgments

We wish to thank Preston's grandson, Professor Thomas Preston and other members of the Preston family, the Royal Dublin Society, Professor Bruce Hunt, the late Professor T. E. Nevin, and Professor P. K. Carroll for their assistance.

Appendix: Theory of the Zeeman Effect

Classical Theory

The classical theory of radiation developed by Lorentz and Larmor was based on the idea of an electron oscillator (or an even vaguer 'molecule') in periodic motion of frequency ν, which emitted radiation of the same frequency. The electron oscillator would, in the absence of magnetic fields, have orbital motions of a single frequency randomly oriented in space. This motion can be resolved into component parts so that if a magnetic field is applied in the z direction, three kinds of simple harmonic motion are expected. These would be a linear vibration along the z axis and circular motions clockwise and anticlockwise about the z axis as shown in Figure 7. The effect of the magnetic field would be to speed up one of the circular motions and slow down the other. The electron oscillator would thus have three different frequencies associated with it.

Now consider observation perpendicular and parallel to the magnetic field, i.e. *transverse* and *longitudinal* observation. For the transverse case the unchanged frequency will appear to be linearly polarized parallel to the magnetic field since it

---

[37] Obituary notice for Thomas Preston, *Physical Review*, 11 (1900), 188. His portrait faces p. 129.

[38] Obituary notice for George Francis Fitzgerald, *Physical Review*, 12 (1901), 292–313.

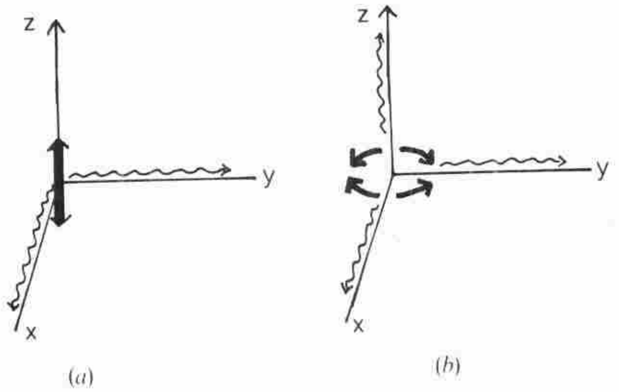


Figure 7. (*a*) the heavy line represents the component of the electron oscillator's motion along the direction of an applied magnetic field. The wavy lines represent radiation. Note that no radiation is emitted in the direction of the magnetic field. (*b*) the heavy lines represent the circular components of the electron oscillator's motion around the direction of an applied magnetic field. The wavy lines represent radiation.

originates from the electron oscillator vibrating in the direction of the field. For the circular motions in the xy plane only the oy components would be expected to emit radiation in the x direction. Hence the circular motions were expected to give radiation linearly polarized perpendicular to the magnetic field. Further the radiations were expected to differ from the original in frequency by

$$\Delta\nu = \pm \frac{eB}{4\pi mc} \tag{1 a}$$

and in wavelength by

$$\Delta\lambda = \pm \frac{eB}{4\pi mc^2}\lambda^2 \tag{1 b}$$

For longitudinal observation no light was expected from oscillators vibrating along the field direction whereas the electrons moving in circular orbits would be expected to emit circularly polarized light in the z direction.

The expected situation is summarized in Figure 8. The threefold splitting predicted for transverse observation became known as the Lorentz triplet and played a central role in early discussion of the Zeeman Effect.

Quantum Theory

The quantum mechanical approach sees the Zeeman Effect arising from an interaction between an external magnetic field and a quantity known as the magnetic moment of the atom. The magnetic moment has its origin in the orbital and spin angular momenta of the electrons and in circumstances where the resultant orbital angular momentum L and the resultant spin angular momentum S are well defined the magnetic moment is given by

$$\bar{\mu} = -\frac{\mu_B}{\hbar}[\bar{L} + 2\bar{S}] \tag{2}$$

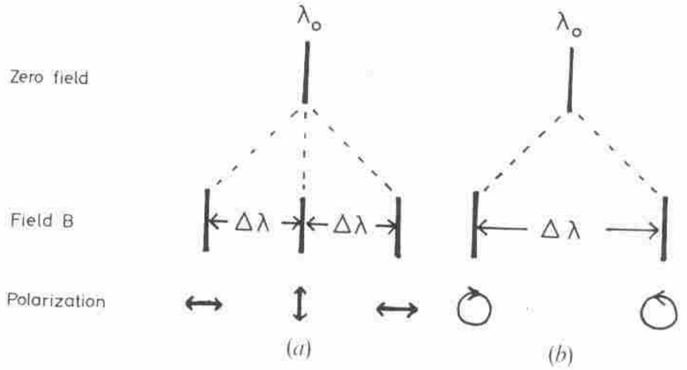


Figure 8. λ_0 represents the wavelength of the line in zero field. $\Delta\lambda$ represents the change in wavelength given by equation (1 *b*) for a source in a magnetic field. (*a*) refers to transverse observation. The triplet components are expected to be linearly polarized, as indicated, with the central component polarized in the direction of the magnetic field. (*b*) refers to longitudinal observation. Only two components are predicted and both are expected to be circularly polarized.

where $\mu_B = eh/2m_e c$ is known as the Bohr magneton. The interaction energy takes the form

$$\Delta E = -\bar{\mu}.\bar{B} \tag{3}$$

which in terms of quantum mechanical magnitudes may be written

$$\Delta E = g\mu_B B M_J \tag{4}$$

where

$$g = \left[1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}\right]$$

is called the Landé g factor and M_J is the quantized projection of the total angular momentum vector J along the direction of the magnetic field. It ranges in integer steps from $-J$ to J.

The interaction with the magnetic field removes the $(2J+1)$-fold degeneracy of an energy level, resulting in $2J+1$ components equally spaced in energy by the value $g\mu_B B$. Before illustrating the predictions of quantum theory with a few examples particularly relevant to the early history of the Zeeman Effect it is necessary to make a few general points. In considering transitions which may occur between the Zeeman components of two energy levels one must take account of the usual selection rules governing transitions between the non-split levels and in addition the rule $\Delta M_J = 0 \pm 1$ (subject to $M_J = 0 \nrightarrow M_J = 0$ if $\Delta J = 0$). Theory further shows that the transitions with $\Delta M = \pm 1$ (called σ components) are circularly polarized in longitudinal observation and plane polarized in the xy plane for transverse observation. The $\Delta M = 0$ transitions (called π components) are absent in longitudinal observation and plane polarized along the z axis for transverse observation.

We will now illustrate the predictions of quantum theory by considering some examples including a number of the spectrum lines used in the early work of Zeeman, Preston, Cornu, and Michelson:

(*a*) *Singlet terms.* For singlet terms $g=1$ and therefore any splitting between components will take the value $\mu_B B$ (approximately 0·467 cm^{-1} for a field of 10^4 Gauss or 1 Tesla). (See Table 1.)

Level	g	gM_J
$^1S_0$	1	0
$^1P_1$	1	1, 0, −1
$^1D_2$	1	2, 1, 0, −1, −2
$^1F_3$	1	3, 2, 1, 0, −1, −2, −3

Table 1. Landé g factors and splitting factors gM_J for singlet terms.

Although a multiplicity of transitions may occur between the Zeeman components of singlet levels the observed spectrum always takes the appearance of the so-called 'normal Zeeman' pattern, i.e. it conforms to the pattern originally predicted by classical theory. The reason for this may be seen in the diagram in the appendix depicting a $^1P_1$–$^1D_2$ transition. (See Figure 9.)

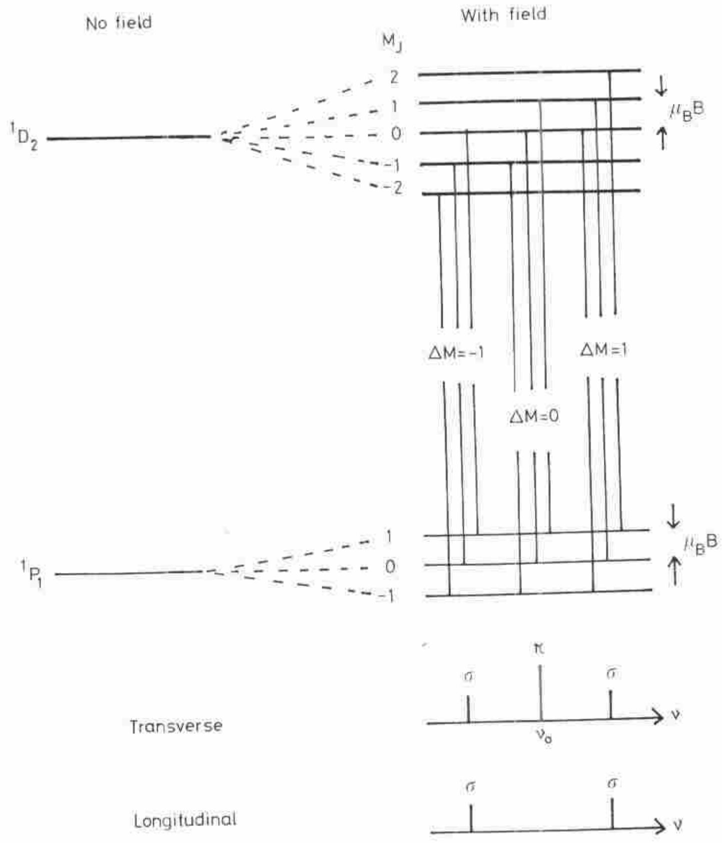


Figure 9. This is an example of a singlet transition ($^1P_1$–$^1D_2$). The upper part of the diagram shows the splitting of the levels in a magnetic field and the allowed transitions. The lower part shows the line structure which is expected for transverse and longitudinal observation. The expected polarization and intensity of the components is also indicated.

Thus in the illustration the Zeeman pattern for transverse observation is due to nine distinct transitions but the observed spectrum consists of only three lines because of identical magnetic splittings in the upper and lower levels. The red line of cadmium at 6438·47 Å is due to a ${}^1P_1$–${}^1D_2$ transition and was one of the lines studied in early Zeeman work.

(*b*) *Doublet terms.* For doublet terms the Landé g factor varies from one term to another with a consequential variation in magnetic splitting. Some values are shown in Table 2.

Level	g	gM_J
${}^2S_{1/2}$	2	1, −1
${}^2P_{1/2}$	2/3	1/3, −1/3
${}^2P_{3/2}$	4/3	2, 2/3, −2/3, −2
${}^2D_{3/2}$	4/5	6/5, 2/5, −2/5, −6/5
${}^2D_{5/2}$	6/5	15/5, 9/5, 3/5, −3/5, −9/5, −15/5

Table 2. Landé g factors and splitting factors gM_J for doublet terms.

The example we will give is the sodium doublet due to a ${}^2S_{1/2}$–${}^2P_{1/2,\,3/2}$ transition. These lines were examined by most if not all the early workers on the magnetic splitting of spectrum lines. The energy level structure and expected spectrum (on the basis of quantum theory) is shown. (See Figure 10.)

(*c*) *Triplet terms.* For triplet terms and indeed all higher multiplicity terms the value of g varies from one term to another. Some values relevant to our discussion are shown in Table 3.

Level	g	gM_J
${}^3S_1$	2	2, 0, −2
${}^3P_0$	0	0
${}^3P_1$	3/2	3/2, 0, −3/2
${}^3P_2$	3/2	6/2, 3/2, 0, −3/2, −6/2

Table 3. Landé g factors and splitting factors gM_J for triplet terms.

Much early work concentrated on the cadmium (λ4678, λ4800, λ5085) and zinc (λ4680, λ4722, λ4811) triplets which are due to transitions of the type ${}^3S_1$–${}^3P_{0,1,2}$. The energy level structure and expected spectrum is shown. (See Figure 11.)

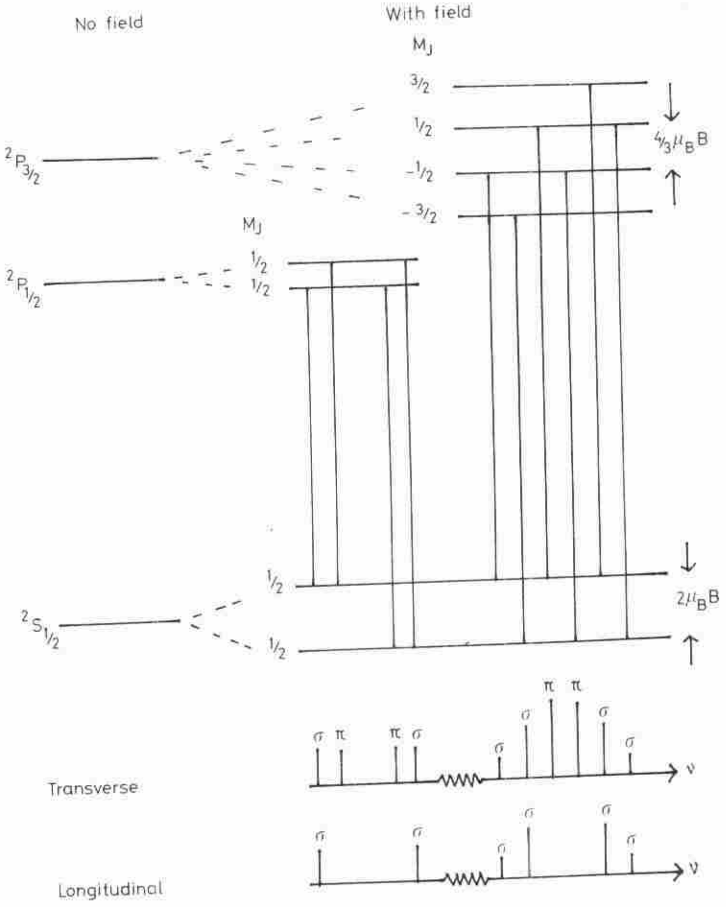


Figure 10. This is an example of a doublet transition ($^2S_{1/2}$–$^2P_{1/2,3/2}$). Other details as for Figure 9.

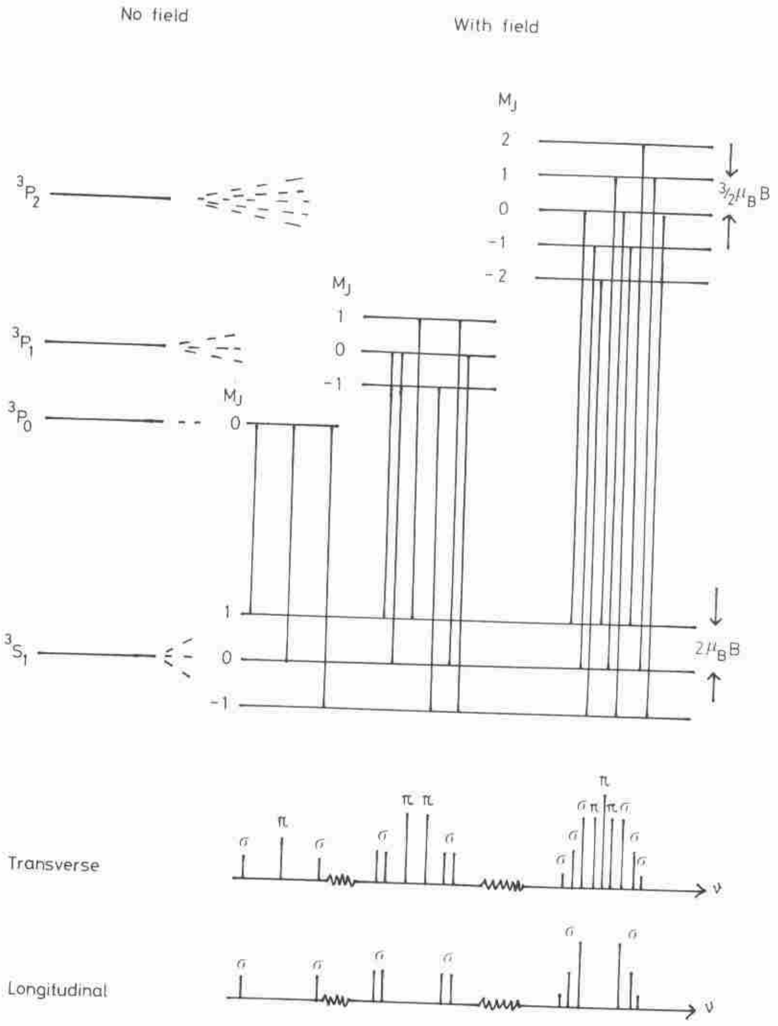


Figure 11. This is an example of a triplet transition ($^3S_1$–$^3P_{0,1,2}$). Other details as for Figure 9.