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THE DISCOVERY OF THE ZEEMAN EFFECT: A CASE STUDY OF THE INTERPLAY BETWEEN THEORY AND EXPERIMENT

1. Introduction

THE ANALYSIS of experimentation is a relatively new trend in history and philosophy of science. After the demise of logical positivism both disciplines tended to focus on the theoretical aspects of science and played down the autonomy and importance of experimental life. The theoretical orientation of post-positivistic studies of science and their concomitant 'neglect of experiment' has been criticized on both historical and philosophical grounds. A group of historians and philosophers of science has recently protested against the neglect of experiment and instrumentation, and attempted a historical and philosophical exploration of experimental science. The outcome of this criticism is a developing experiment-orientated history and philosophy of science.[1]

Three aspects of the historical and philosophical commentary on experimentation deserve special mention. First, the focus of analysis has moved away

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[1]The pioneering step in this direction was made by Ian Hacking, *Representing and Intervening* (Cambridge: Cambridge University Press, 1983). Other significant contributions to the same subject include Peter Achinstein and Owen Hannaway (eds), *Observation, Experiment, and Hypothesis in Modern Physical Science* (Cambridge, Massachusetts: MIT Press, 1985); Allan Franklin, *The Neglect of Experiment* (Cambridge: Cambridge University Press, 1986); Peter L. Galison, *How Experiments End* (Chicago: University of Chicago Press, 1987); David Gooding, Trevor Pinch, and Simon Schaffer (eds), *The Uses of Experiment: Studies in the Natural Sciences* (Cambridge: Cambridge University Press, 1989); the collection of essays in Timothy Lenoir and Yehuda Elkana (eds), 'Practice, Context, and the Dialogue between Theory and Experiment', *Science in Context* **2** (1988) No. 1; and Steven Shapin and Simon Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life* (Princeton, New Jersey: Princeton University Press, 1985). For a recent overview of the philosophy of experiment see Ian Hacking, 'Philosophers of Experiment', in Arthur Fine and Jarrett Leplin (eds), *PSA 1988: Proceedings of the 1988 Biennial Meeting of the Philosophy of Science Association*, Vol. 2 'Symposia and Invited Papers' (East Lansing, Michigan: Philosophy of Science Association, 1989), pp. 147–156. Another useful and up to date survey of studies of experimentation, which focuses on works written from a sociological perspective, is Jan Golinski, 'The Theory of Practice and the Practice of Theory: Sociological Approaches in the History of Science', *Isis* **81** (1990), 492–505.

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from the end-product of experimental practice (experimental results and observational reports) and towards the experimental process itself. It is this emphasis on the process which leads to the discovery and consolidation of experimental facts that distinguishes recent historical and philosophical work from earlier positivistic fascination with 'raw' observational data.[2]

Second, the revival of interest in experimentation has led to the realization that experimental practice is richer than theory-testing. This amounts to a denial of the view, exemplified by Karl Popper, that the role of experiment is to corroborate or falsify precisely formulated theoretical predictions.[3] Despite the importance that Popper attached to observation, he downplayed the autonomy and exploratory character of the experimental activity. The new 'experimental' philosophy on the other hand, denies that there must "be a conjecture under test in order for an experiment to make sense".[4] There is an element of exploration in experimental practice which is not subservient to theoretical anticipations.

Third, the historico-philosophical examination of experimental activity has led to a reappraisal of the well known problem of the 'theory-ladenness' of observation.[5] Few historians and philosophers of experiment would be willing to deny that observation and experimentation are theory-guided activities. Even those who, like Ian Hacking, assert "the existence of pretheoretical observations or experiments"[6] do not deny that observation has a 'theoretical' dimension, namely a web of beliefs which are associated even with the most elementary observations. They deny, however, that this dimension is necessarily part of a developed and articulated theoretical construct. If by 'theory'

[2]Ian Hacking, for instance, denies the importance of observation: "Observation, as a primary source of data, has always been a part of natural science, but it is not all that important". (Hacking, *Representing*, *op. cit.*, note 1, p. 167.) He moves instead the emphasis from observation to experimental practice: "Often the experimental task . . . is less to observe and report, than to get some bit of equipment to exhibit phenomena in a reliable way". (*Ibid.*) An essential aspect of this practice "*is getting to know when the experiment is working*. That is one reason why observation in the philosophy-of-science usage of the term, plays a relatively small role in experimental science. Noting and reporting readings of dials — Oxford philosophy's picture of experiment — is nothing. Another kind of observation is what counts: *the uncanny ability to pick out what is odd, wrong, instructive or distorted in the antics of one's equipment*." (*Ibid.*, p. 230; emphasis added.)

[3]"The theoretician puts certain definite questions to the experimenter, and the latter, by his experiments, tries to elicit a decisive answer to these questions, and to no others. . . . [T]he theoretician must long before [the experimenter] have done his work, or at least what is the most important part of his work: he must have formulated his question as sharply as possible". K. R. Popper, *The Logic of Scientific Discovery* (New York: Harper & Row, 1968), p. 107.

[4]Hacking, *Representing*, *op. cit.*, note 1, p. 154.

[5]The problem was introduced by N. R. Hanson in the late 1950s and widely propagated by Thomas Kuhn and Paul Feyerabend in the following decades. See N. R. Hanson, *Patterns of Discovery* (Cambridge: Cambridge University Press, 1958); T. S. Kuhn, *The Structure of Scientific Revolutions*, 2nd edn (Chicago: University of Chicago Press, 1970); and P. Feyerabend, *Against Method* (London: New Left Books, 1975).

[6]Hacking, *Representing*, *op. cit.*, note 1, p. 150.

we mean a systematic body of knowledge then the history of science offers a plethora of pretheoretical observations and experiments. Thus, before discussing the theory-ladenness issue it is imperative to realize that there are many levels of theory, ranging from qualitative speculations to formalized and systematic constructs, which influence experimental practice in different ways.[7] The differentiation between several levels of theory is closely connected with the denial of the post-positivistic thesis that the theory-ladenness of the experimental process hinders the evaluation and testing of theories. The background knowledge involved in the construction and description of an experiment need not coincide with the theory under examination.[8] Part of this background knowledge is the theory(ies) of the instrument(s) which constitute the experimental set-up. As a matter of fact, "[s]eldom (never?) is the phenomenological theory of an instrument the same as the theory in question".[9] Thus, since our procedures of obtaining experimental results are not necessarily laden with the theory under examination, no threat is posed, at least in principle, to the possibility of theory testing.[10]

[7]For an elaborate version of this view see Hacking, *Representing*, *op. cit.*, note 1, pp. 212–219. Peter Galison also distinguishes between various levels of theoretical commitment and argues that each level affects the experimental process in a different way. See Galison, *Experiments*, *op. cit.*, note 1, pp. 244–257.

[8]See, for instance, Allan Franklin, *The Neglect*, *op. cit.*, note 1, pp. 109–113. John Greenwood has capitalized on this very point to argue persuasively that the theory-ladenness of observation does not imply incommensurability between competing theories, and therefore does not pose any threat to the possibility of their comparative evaluation. See J. D. Greenwood, 'Two Dogmas of Neo-Empiricism: The "Theory-Informity" of Observation and the Quine–Duhem Thesis', *Philosophy of Science* **57** (1990), 553–574.

[9]Ian Hacking, 'On the Stability of the Laboratory Sciences', *The Journal of Philosophy* **85** (1988), 507–514, on p. 510. Robert Ackermann has also argued that the interpretation of experimental data depends on the understanding of the instruments employed for their acquisition and not on the high-level theory under investigation. It is for this reason that instruments "break the line of influence from interpretation to observation, or from theory to fact" (p. 129). See R. J. Ackermann, *Data, Instruments, and Theory: A Dialectical Approach to Understanding Science* (Princeton, New Jersey: Princeton University Press, 1985), pp. 129–136. Even if the two theories coincide, however, one could calibrate the instrument in use "against another [similar instrument] . . . whose operation depends on a different theory. . . . Calibration, in this instance, serves to transfer the theory of the apparatus from the theory under test." Allan Franklin *et al.*, 'Can a Theory-Laden Observation Test the Theory?', *British Journal for the Philosophy of Science* **40** (1989), 229–231, on p. 230.

[10]In the above discussion and throughout this paper I have tacitly assumed the commonly held view that the possibility of theory-testing would be eliminated if the theory employed in setting up an experiment were the same as the theory that the experiment was designed to test. However, as Dudley Shapere pointed out, this view is mistaken. The "fact [that the theory under test and the theory which informs the experimental process coincide] by no means make it impossible that . . . [this] theory might be questioned, modified, or even rejected as a consequence of the experiment. It is not a logical or necessary truth that it could be so questioned; but *as a matter of fact*, we find that, despite the employment of the same theory . . . disagreement between prediction and observation results. And that disagreement could eventuate in the alteration or even rejection of . . . [the] theory despite its pervasive role in determining the entire observation-situation." See D. Shapere, 'The Concept of Observation in Science and Philosophy', *Philosophy of Science* **49** (1982), 485–525, on p. 516.

What has been said can be condensed in Hacking's aptly chosen slogan: "Experimentation has a life of its own".[11] The autonomy of experimental life implies that the traditions within experiment and theory do not usually go together. As Peter Galison has argued, "there are only piece-wise connections between the different strata [theoretical and experimental], not a total convergence or reduction".[12]

The goal of this paper, though relevant to the issues discussed above, is not primarily the elucidation of philosophical problems by means of a historical study of a scientific episode. It is rather the understanding of the multiplicity of factors which shape the experimental process. The core of my analysis concerns the discovery and initial explanation of the Zeeman effect — the splitting of spectral lines when their source is placed under the influence of a magnetic field — and aims at showing in what ways Zeeman's experimental practices had an exploratory character and an autonomy from the highly formalized electromagnetic theories of his time.

Three main themes constitute the backbone of my narrative. Its starting point is Zeeman's motivation in undertaking an experimental investigation about the influence of magnetism on light and his debt to late-nineteenth-century magneto-optical research. I continue with considering how Zeeman employed background knolwedge of the connection between magnetism and light for the construction of his experimental set-ups. The focus of the discussion is on his strategy in eliminating background effects, which might distort the outcome of his experiments, and thus producing experimental results which would convincingly establish the direct action of magnetism on light. This strategy, along with the technological resources at Zeeman's disposal, suffice to explain why Zeeman succeeded where others had failed to demonstrate the phenomenon named after him. Finally, I examine the role of theoretical background, ranging from qualitative speculations to concrete quantitative models, in various stages of the experimental process and argue that the early phases of Zeeman's experimental investigations were independent of high-level theoretical constructs; formalized electromagnetic theory exerted an influence only in the later stages of Zeeman's research. The paper concludes with the implications of the historical analysis for the ongoing debate in history and philosophy of science over the relation between theory and experiment.

[11]Hacking, *Representing*, *op. cit.*, note 1, p. 150.

[12]Peter Galison, 'Philosophy in the Laboratory', *The Journal of Philosophy* **85** (1988), 525–527, on p. 526. The historiographical implications of the autonomy of experimentation and especially the need for a distinct periodization of theoretical and experimental traditions are discussed in P. Galison, 'History, Philosophy, and the Central Metaphor', *Science in Context* **2** (1988), 197–212.

2. Magneto-Optical Investigations[13] and Zeeman's Early Attempts to Trace the Influence of Magnetism on a Source of Light

It was known since the middle of the nineteenth century that there was a close connection between magnetism and light. In 1845 Michael Faraday demonstrated experimentally that the plane of polarization of light would rotate when sent through substances placed in a magnetic field.[14] Several years later J. Kerr observed polarization changes accompanying the reflection of light from the poles of a magnet.[15] Moreover, Faraday, guided by his theory of light,[16] had looked for a modification in the light emitted by a substance under the influence of a magnetic field, but was unable to detect any effect with the means at his disposal.[17] As Maxwell mentioned in his biographical sketch of Faraday in the *Encyclopaedia Britannica*, "He endeavoured, but in vain, to detect any change in the lines of the spectrum of a flame when the flame was acted on by a powerful magnet".[18] This was Faraday's final experimental investigation: an investigation which met with no success.[19] However, as

[13]My account of magneto-optical researches in the second half of the nineteenth century treats only the magneto-optical investigations which formed part of Zeeman's problem situation. For a detailed discussion of nineteenth-century magneto-optics see J. Brookes Spencer, 'On the Varieties of Nineteenth Century Magneto-Optical Discovery', *Isis* **61** (1970), 34–51. Another useful and highly technical treatment of late-nineteenth-century continental research in magneto-optics can be found in Jed Z. Buchwald, *From Maxwell to Microphysics: Aspects of Electromagnetic Theory in the Last Quarter of the Nineteenth Century* (Chicago: University of Chicago Press, 1985), pp. 205–266.

[14]M. Faraday, 'On the Magnetization of Light and the Illumination of Magnetic Lines of Force', *Philosophical Transactions of the Royal Society* **136** (1846), 1–20. (Read 20 November 1845.)

[15]Kerr announced his discovery at the meeting of the British Association in Glasgow in 1876, and a report of it appeared the following year in the Philosophical Magazine. See J. Kerr, 'On Rotation of the Plane of Polarization by Reflection of the Pole of a Magnet', *London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 5th series **3** (1877), 321–343.

[16]Faraday regarded "radiation as high species of vibration in the lines of force which are known to connect particles and also masses of matter together". See Michael Faraday, 'Thoughts on Ray Vibrations', *London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 3rd series **28** (1846), 345–350, on p. 348. Identifying light with vibrations of the lines of force, Faraday had good reasons to believe that the action of magnetism might modify the spectrum of a radiating substance.

[17]As Zeeman remarked many years later, "The technique of obtaining strong magnetic fields and powerful spectroscopes was, however, inadequately worked out at the time." P. Zeeman, 'Faraday's Researches on Magneto-Optics and their Development', *Nature* **128** (1931), 365–368, on p. 366.

[18]J. C. Maxwell, 'Faraday', in W. D. Niven (ed.), *The Scientific Papers of James Clerk Maxwell*, 2 vols (New York: Dover, 1952), Vol. 2, pp. 786–793, on p. 790.

[19]As we read in *Faraday's Diary*, "the Electro magnet was excited and rendered neutral; but not the slightest effect on the polarized or unpolarized ray was observed.". T. Martin (ed.), *Faraday's Diary*, 7 vols (London: G. Bell & Sons, 1932–36), Vol. 7, p. 465.

Whittaker remarked in his *History of the Theories of Aether and Electricity*, the belief that a phenomenon "of this nature remained to be discovered, was shared by many of his successors".[20]

P. G. Tait had made several fruitless attempts to trace the influence of magnetism on a substance's spectral lines. In 1875 he published a note in which he mentioned his experimental investigations on this subject, and revealed the theoretical considerations which had induced him to engage in research of this kind.[21] These considerations were founded on William Thomson's theory of the molecular rotation of the ether. As Tait recalled:

> The explanation of Faraday's rotation of the plane of polarization of light by a transparent diamagnetic requires, as shown by Thomson, molecular rotation of the luminiferous medium. The plane-polarized ray is broken up, while in the medium, into its circularly-polarized components, one of which rotates with the aether so as to have its period accelerated, the other against it in a retarded period. Now, suppose the medium to absorb one definite wavelength only, then — if the absorption is not interfered with by the magnetic action — the portion absorbed in one ray will be of a shorter, in the other of a longer, period than if there had been no magnetic force; and thus, *what was originally a single dark absorption line might become a double line, the components being less dark than the single one*. [Emphasis added.][22]

According to Thomson's model,[23] the magnetic field makes the molecules of the transparent medium rotate around a line parallel to the lines of magnetic force. A plane-polarized ray, while transmitted through the medium, is resolved into two circularly-polarized components which rotate in opposite directions. Therefore, the rotation of the medium accelerates the one component and decelerates the other. If the medium under consideration absorbs radiation of a certain frequency, then the portions absorbed in both components will correspond to the same frequency. However, when the two components escape the influence of the magnetized medium and return to their former condition they will have suffered absorption at different frequencies.[24] Hence one should expect the appearance of a double absorption line instead of a single one.

[20]E. Whittaker, *A History of the Theories of Aether and Electricity*, 2 vols (New York: Harper Torchbooks, 1960), Vol. I, p. 410.

[21]P. G. Tait, 'On a Possible Influence of Magnetism on the Absorption of Light, and Some Correlated Subjects', *Proceedings of the Royal Society of Edinburgh* **9** (1875), 118.

[22]*Ibid.*

[23]William Thomson, 'Dynamical Illustrations of the Magnetic and the Helicoidal Rotatory Effects of Transparent Bodies on Polarized Light', *Proceedings of the Royal Society of London* **8** (1856), 150–158.

[24]Suppose that the original frequency band of the two components is $[f_1, f_2]$. The rotation of the medium displaces the two components to a higher and a lower frequency band respectively, i.e. $[f_1+f_x, f_2+f_x]$, $[f_1-f_x, f_2-f_x]$. The medium absorbs a certain frequency, say f_y. When the components return to their initial condition, the absorbed frequency from the higher band will return to f_y-f_x and the absorbed frequency from the lower band will return to f_y+f_x.

Ten years after Tait's publication, Ch. Fievez published two papers which contained experiments along the same lines as Zeeman's experimental discovery.[25] It is important to note that the observations reported by Fievez were in some cases incompatible with Zeeman's experimental results. After discussing the various aspects of Zeeman's discovery, I will consider the implications of the above incompatibility for the understanding of the process by which experimental data acquire significance.

Pieter Zeeman (1856–1943)[26] entered the University of Leiden in 1885 and was trained by Kamerlingh Onnes and H. A. Lorentz. In 1890 he became Lorentz's assistant and commenced his investigations on the Kerr effect — the rotation of the plane of polarization of light upon reflection from the poles of a magnet.[27] In the early 1890s he interrupted his experimental research on the Kerr phenomenon,[28] in order to attempt to detect the influence of a magnetic field on the spectrum of a sodium flame. This idea was motivated, as in Tait's case, by Kelvin's and Maxwell's model of the ether, which entailed that in a magnetic field a rotatory motion of the ether takes place around the direction of the magnetic force. It should be emphasized, however, that at that time Zeeman was unaware of Tait's attempts. His results were negative, and, as he mentioned a few years later in the first report of his discovery,

> I should not have tried this experiment again soon had not my attention been drawn some two years ago to . . . Maxwell's sketch of Faraday's life . . . If a Faraday thought of the possibility of the above mentioned relation [between magnetism and light], perhaps it might yet be worthwhile to try the experiment again with the excellent auxiliaries of the spectroscopy of the present time, as I am not aware that it has been done by others.[29]

Thus, Faraday's authority as an experimenter was a significant factor in Zeeman's decision to continue his experimental investigations on the effect of magnetism on the spectral characteristics of light.[30] So, early in 1896 he repeated the experiment, but his attempt to demonstrate the action of magnetism on light proved once more unsuccessful.

[25]Ch. Fievez, 'De l'influence du magnétisme sur les caractères des raies spectrales', *Bulletins de l'Academie Royale des Sciences, des Lettres et des Beaux-Arts de Belgique* 3rd series **9** (1885), 381–385. Ch. Fievez, 'Essai sur l'origine des raies de Fraunhofer, en rapport avec la constitution du Soleil', *ibid.* 3rd series, **12** (1886), 25–32.

[26]For a short biographical essay on Zeeman see Kostas Gavroglou, 'Pieter Zeeman', in *The Nobel Prize Winners: Physics* (Pasadena, California: Salem Press, 1989), pp. 45–52.

[27]Zeeman probably "chose magneto-optics as a topic because Lorentz was deeply concerned with the phenomenon during this period". Buchwald, *From Maxwell, op. cit.*, note 13, p. 200.

[28]For his measurements of the Kerr effect Zeeman was awarded the gold medal of the Netherlands Scientific Society of Haarlem in 1892.

[29]P. Zeeman, 'On the Influence of Magnetism on the Nature of the Light Emitted by a Substance (Part I)', *Communications from the Physical Laboratory at the University of Leiden* **33** (1896), 1–8, on p. 3.

[30]Several years later Zeeman referred to Faraday as "the greatest experimental genius the world has produced". P. Zeeman, *Researches in Magneto-Optics: With Special Reference to the Magnetic Resolution of Spectrum Lines* (London: Macmillan, 1913), p. xi.

3. Background Knowledge and Zeeman's Initial Discovery

Meanwhile, the Physical Laboratory of the University of Leiden bought a concave Rowland grating with greater resolving power than the gratings then in use.[31] Therefore, Zeeman decided to try the experiment again. This time his tenacity was finally rewarded. Let us examine more closely this experimental episode which proved decisive for many later developments in physics.

The equipment that Zeeman used included a Rühmkorff electromagnet,[32] a set of accumulators to provide the magnetizing current, a Rowland grating with a radius of 10 foot and with 14 438 lines per inch to obtain the spectrum observations, and a Bunsen burner. He placed the flame of the burner between the poles of the electromagnet and held a piece of asbestos impregnated with common salt in the flame. After turning on the electromagnet the two D-lines of the sodium spectrum, which had been previously narrow and sharply defined, were clearly widened. In shutting off the current the lines returned to their former condition (see Fig. 1[33]). Zeeman then replaced the Bunsen burner with a flame of lightgas fed with oxygen and repeated the experiment. The D-lines were again broadened, becoming three or four times wider. Replacing the sodium by lithium he observed the same phenomena.

These initial and elementary stages of Zeeman's experiment already reveal the presuppositions of his experimental procedures. The variables of an experiment are, strictly speaking, innumerable. In the above experiment, for example, these variables include the intensity of the magnetic field, the

[31]The grating is an instrument which produces spectra by a combination of diffraction and interference. Its characteristics are described in H. A. Rowland, 'On Concave Gratings for Optical Purposes', *Philosophical Magazine* **16** (1883), 197–210. A concise account of the Rowland concave grating is found in Zeeman's Nobel lecture: "[A] polished metal mirror with a very large number of grooves, say 50 000 over a width of 10 cm scratched on by means of a diamond. A beam of compound light is no longer reflected by the lined surface in the ordinary way; instead each special kind of light follows its own path. . . . A further main advantage of Rowland's grating is that it is now no longer scratched on plain surfaces, but on spherical concave surfaces with a radius of say 3 metres, so that real images are produced of luminous lines without the need for the insertion of lenses." Pieter Zeeman, 'Light Radiation in a Magnetic Field', Nobel Lecture, 2 May 1903, in *Nobel Lectures: Physics 1901–1921* (Amsterdam: Elsevier, 1965), p. 33. See also Zeeman's discussion of the grating in his *Researches*, *op. cit.*, note 30, pp. 1–13.

[32]An electromagnet whose design was due to H. D. Rühmkorff (1803–1877), an instrument maker who invented an induction coil that could generate a very strong electromotive force. See Bernard Finn's article on Rühmkorff in C. C. Gillispie (ed.), *Dictionary of Scientific Biography*, 16 vols (New York: Charles Scribner's Sons, 1970–1980).

[33]From Thomas Preston, 'Radiation Phenomena in a Strong Magnetic Field', *The Scientific Transactions of the Royal Dublin Society* 2nd series **6** (1898), 385–392, on p. 392. (Read 22 December 1897.) Preston was the first to publish photographs of the Zeeman effect. Zeeman, who a few months after his initial discovery moved to the University of Amsterdam, could not photograph the effect because of "the instability of the mounting of the spectrum apparatus" (Zeeman, *Researches*, *op. cit.*, note 30, p. 55). "Of thirty photographs, at most one could be used. . . . As there was no hope of obtaining a more stable arrangement for want of funds and room, I was obliged, to my great regret, to abandon for the time being my attempts to photograph the whole spectrum". (*Ibid.*, p. 57.)

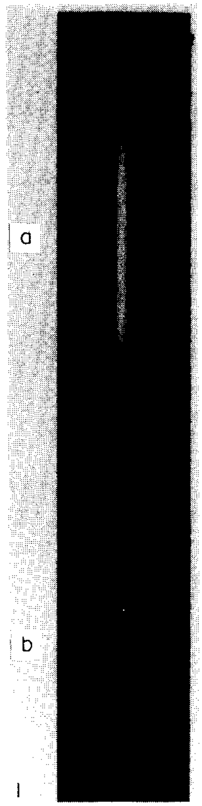

Fig. 1. "[T]he effect produced on the violet line of cadmium . . . . At the top, a, we have the line photographed with the magnet unexcited . . . . Underneath this, at b, the same line is photographed with the magnet excited. . . . It accordingly appears to be . . . broadened by the magnetic field".[33]

resolving power of the grating, the characteristics of the flame, the chemical composition of the radiating substance, the spatial arrangement of the instruments, as well as innumerable 'irrelevant' factors, like the dimensions of the room in which the experiment was performed, the room's temperature and humidity, and so on. The experimenter alters only a few of all the possible variables. The inevitable selection is determined by the experimenter's presuppositions about the significance of each variable for the experiment's outcome. Background knowledge is instrumental in the construction and execution of any experiment. The discussion of the next stage of Zeeman's experiment will show more specifically how background knowledge is employed in order to identify and eliminate effects which could diminish the persuasive power of the experiment.

Zeeman was not convinced that the observed widening was due to the action of the magnetic field directly upon the emitted light. The effect could be caused by an increase of the radiating substance's density and temperature. A similar

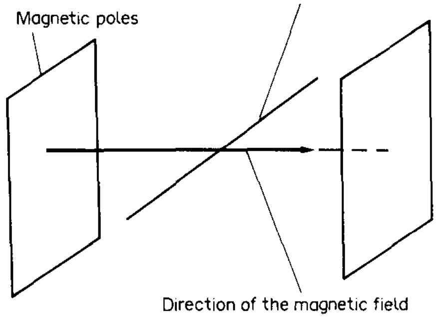

Fig. 2.

phenomenon had been reported by E. Pringsheim in 1892.[34] This already established experimental knowledge prevented Zeeman from ending his experiment at this stage. Since the magnet caused an alteration of the flame's shape, a subsequent change of the flame's temperature and density was also possible. Therefore, Zeeman tried another much more complicated experiment. He put a porcelain tube horizontally between the poles of the electromagnet, with the tube's axis perpendicular to the direction of the magnetic field (see Fig. 2). Two transparent caps were attached to each terminal of the tube and a special arrangement was used in order to keep their temperature low even if the tube were rendered incandescent. A piece of sodium was introduced into the tube and simultaneously the tube's temperature was raised by the Bunsen burner. At the same time the light of an electric lamp was guided by a metallic mirror to traverse the entire tube.

It is important to note that in his description of the above experiment Zeeman mentioned several details that reveal the parameters of the experimental process he considered important for the experiment's outcome. Their inclusion in Zeeman's paper was probably made, among other reasons, in order to facilitate the precise reproduction of the experiment by other scientists.[35] These details include the inner and outer diameters of the tube, the tube's length, the composition of its inner surface, the portion of the tube which was made incandescent, the exact position of the lamp and the distance

[34]E. Pringsheim, 'Kirchhoff'sches Gesetz und die Strahlung der Gase', *Wiedmannsche Annalen der Physik* **45** (1892), 428–459, on pp. 455–457.

[35]It was not unusual for Zeemann to include detailed information about the instruments employed in his experiments. See, e.g., P. Zeeman, 'Measurements Concerning KERR's Phenomenon with Normal Polar Reflection from Iron and Cobalt', *Communications from the Physical Laboratory at the University of Leiden* **15** (1895), 1–15, pp. 6–8. However, it seems that the parameters mentioned by Zeeman were not used for reproduction purposes, since Oliver Lodge, who confirmed Zeeman's observations, repeated only those of Zeeman's experiments which concerned the influence of magnetism on the emission spectrum of a substance.

between the poles of the electromagnet.[36] Other parameters of the experiment, like the laboratory's temperature and dimensions, the intensity of the light of the electric lamp and the quantity of the sodium used, were completely disregarded. Again, this predilection for certain parameters reveals the background knowledge of the physical mechanisms which could influence the experiment's outcome. For example, the distance between the electric lamp and the electromagnet was important because, as Zeeman admitted, a disturbing action of the magnet on the lamp's arc was possible,[37] whereas it was tacitly assumed that the laboratory's dimensions could not bear on the experiment's outcome.

In the next stage of the experiment the sodium, under the action of the Bunsen flame, began to gasify. The vapour's colour, after passing from violet to blue and green, became invisible to the naked eye. Simultaneously the absorption spectrum was obtained by means of the Rowland grating. Finally the two sharp D-lines of sodium were observed. The heterogeneity of the density of the vapour at different heights of the tube produced a corresponding asymmetry in the lines' width, making them thicker at the top. By activating the electromagnet the lines became broader and darker. When it was turned off the lines recovered their initial form. Repetitions of the experiment caused the sodium to disappear. This was ascribed to the chemical reaction between sodium and the glaze covering the inner surface of the tube. In further experiments Zeeman used unglazed tubes.

Zeeman's experimental scruples were, nonetheless, not satisfied. Remember that the experiment's purpose was to demonstrate the direct effect of magnetism on light. Zeeman was still sceptical about whether this aim had been accomplished. The different temperature in the upper and lower parts of the tube was responsible for the heterogeneity of the vapour's density. The vapour was denser at the top of the tube and, since their width at a certain height depended on the number of incandescent particles at that height, the spectral lines were therefore thicker at the top. It was conceivable that the activation of the magnetic field could give rise to differences of pressure in the tube of the same order of magnitude and in the opposite direction to those produced by the differences of temperature. If this were the case, the action of magnetism would move the denser layers of vapour toward the bottom of the tube and would alter in this way the width of spectral lines without interacting directly with the light that generated the spectrum.

To avoid the undesirable implications of these considerations Zeeman performed an even more refined experiment. He used a smaller tube and heated it with a blowpipe in order to eliminate disturbing temperature differences. Moreover, he rotated the tube around its axis and thus achieved equal

[36]Zeeman, 'Influence of Magnetism (I)', *op. cit.*, note 29, pp. 5–6.
[37]*Ibid.*, p. 6.

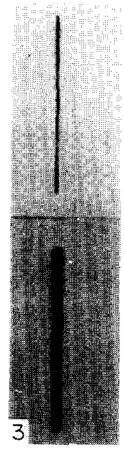

Fig. 3. "a shows the original spectrum line, b the magnetically widened line".[38]

densities of sodium vapour at all heights. The D-lines were now uniformly wide along their whole length. The subsequent. activation of the electromagnet resulted in their uniform broadening (see Fig. 3).[38]

Zeeman was by then nearly convinced that the outcome of his experiments was due to the influence of magnetism directly upon the light emitted or absorbed by sodium: "The different experiments . . . make it more and more probable, that the absorption — and hence also the emission — lines of an incandescent vapour, are widened by the action of magnetism".[39] The sentence immediately following is instructive with respect to the theoretical dimension of Zeeman's experimentation: "Hence if this is really the case, then by the action of magnetism in addition to the free vibrations of the *atoms, which are the cause of the line spectrum*, other vibrations of changed period appear"[40] (emphasis added).

It is evident that Zeeman identified the origin of spectral lines with the vibration of atoms. Two theories at that time — Larmor's theory of radiation and Lorentz's electromagnetic theory — accounted for the emission of light in this way and Zeeman was certainly aware, as the above excerpt demonstrates, of at least one of them.[41] However, Zeeman, several years later, denied the dependence of his discovery on any special theory and stressed the exploratory character of his experiment: "Quite independently of a special theory, I had the idea that when the forces acting during the propagation of light in the Faraday

[38]From Zeeman, *Researches*, *op. cit.*, note 30, p. 35.
[39]Zeeman, 'Influence of Magnetism (I)', *op. cit.*, note 29, p. 8.
[40]*Ibid.*
[41]Zeeman was certainly aware of Lorentz's theory, since Lorentz was his mentor and collaborator.

effect were also present in a radiating flame under magnetic influence, some new effect would manifest itself. It might have been otherwise indeed."[42] Zeeman thus suggested that there were no compelling theoretical predictions that showed him the way to his discovery.

If, however, we were to disregard Zeeman's recollections and argue that one of the above theories was instrumental for his discovery, we would be forced to admit that he did not realize the implications of any of these theories. For, according to both of these highly formalized theories, his discovery should have been *impossible*. A popular and concise analysis of Larmor's theory, which illustrates this point, is found in a lecture delivered by Sir Oliver Lodge to the Institute of Metals in 1929:

> Larmor's theory of radiation, before the era of electrons, had shown virtually that if a source of radiation were plunged in a magnetic field, the lines of the spectrum ought to be broadened, because a radiating atom would be influenced by any magnetic field in which that revolving or vibrating atom constituted an electric current. It was well known that an electric current was perturbed by magnetism, and this perturbation ought to show itself in the lines of the emitted spectrum . . . Larmor . . . proceeded . . . to calculate quantitatively how much effect was to be expected; . . . He found it surpassingly small and therefore gave up the quest. He had no idea at that time of anything smaller than an atom that was likely to radiate; *and if it were the whole atom that radiated, the effect of a magnetic field would be hopelessly small; for theory showed that it would depend on the ratio of charge to mass, and the mass of an atom is much too big: nearly 2000 times too big*. [Emphasis added.][43]

The consequences of Larmor's theory precluded Zeeman's discovery, since, according to that theory, the source of radiation, i.e. vibrating atoms, could not be significantly affected by the then available magnetic fields.

Nor should Zeeman's discovery have been possible according to Lorentz's theory. According to this theory, the emission of light was due to the vibrations of small electrically charged particles ('ions'), which are constituents of all material bodies. As it will be shown below (Section 4), it follows from Lorentz's theory that the change in the frequency of vibration of an 'ion' due to the influence of a magnetic field is approximately $eH/2m$ (where e and m are the charge and the mass of the 'ion' respectively and H is the intensity of the magnetic field). Thus, the widening of spectral lines, which is a reflection of the

[42]Zeeman, 'Faraday's Researches', *op. cit.*, note 17, p. 366.

[43]Sir Oliver Lodge, 'States of Mind which Make and Miss Discoveries, with Some Ideas about Metals', *Journal of the Institute of Metals* **41** (1929), 345–377, on pp. 349–350. The accuracy of Lodge's retrospective account is confirmed by an excerpt from his first report of Zeeman's discovery: "Dr. J. Larmor wrote to me [immediately after an abstract of Zeeman's experiment appeared in *Nature* on 24 December 1896] . . . that, indeed, he had already deduced that there must be some effect on the spectral lines, but had concluded that it was probably too small to observe". O. Lodge, 'The Latest Discovery in Physics' *The Electrician* **38** (1897), 568–570, on p. 568.

alteration in the mode of vibration of an 'ion', is proportional to the 'ionic' charge to mass ratio. If this ratio coincided with the corresponding ratio of the ions of electrolysis, the expected effect would have been three orders of magnitude smaller than the effect actually observed by Zeeman. Therefore, the effect of a magnetic field on the ion's motion should have been, at least with the means at Zeeman's disposal, undetectable, since Lorentz's 'ions' had not been distinguished prior to Zeeman's discovery from the electrolytical ions. As Zeeman recalled, when he calculated from the widening of the lines the charge to mass ratio and announced it to Lorentz, the latter's response was: "That looks really bad; it does not agree at all with what is to be expected".[44]

The above considerations lead to the conclusion that Zeeman's initial discovery was indeed independent of the formalized electromagnetic theories of his time. Qualitative ideas on the relation between magnetism and light, rather than the quantitative predictions of a sophisticated theory, induced him to undertake the experimental investigations which culminated in his discovery.

On 28 November 1896, shortly after his first series of experiments, Zeeman published another paper,[45] in which, after establishing further the direct action of magnetism on light, he gave a quantitative report of the broadening of the sodium lines. According to his approximate measurements a magnetic field of 10 000 Gauss produced a widening of the D-lines equal to 2.5% of their distance.

Zeeman's style of presentation gives the impression that everybody, irrespective of observational skills, could observe the widening of the sodium lines. However, this was far from being true. The widening of the lines was approximately two tenths of an Ångström ($1\ \text{Å} = 10^{-10}$ m).[46] As Lord Rayleigh recalled, one year after Zeeman's death, "Zeeman said that he had shown the effect as first observed to his friend and master H. A. Lorentz, *who*

[44]Cited in Zeeman, 'Faraday's Researches', *op. cit.*, note 17, p. 367. I have not been able to locate direct evidence for my claim that the 'ions' were assumed to be identical with the ions of electrolysis (i.e. of an order of magnitude comparable with an atom's). Lorentz, to the best of my knowledge, does not specify anywhere in his writings the charge to mass ratio of his 'ions'. Further indirect evidence is found in Oliver Lodge, 'The History of Zeeman's Discovery and its Reception in England', *Nature* **109** (1922), 66–69, on p. 67. There we read that Larmor "*like everyone else at that time*, . . . considered that the radiating body must be an atom or part of an atom with an $e/m = 10^4$" (emphasis added). Moreover, Zeeman, while discussing various aspects of his discovery, remarked that "[t]he value found [for the charge to mass ratio of the 'ion'] is about 1500 times that of the corresponding value which can be derived for hydrogen from the phenomena of electrolysis. *This was something entirely new in 1896.*" (Emphasis added.) P. Zeeman, *Researches*, *op. cit.*, note 30, pp. 39–40.

[45]P. Zeeman, 'On the Influence of Magnetism on the Nature of the Light Emitted by a Substance (Part II)', *Communications from the Physical Laboratory at the University of Leiden* **33** (1896), 9–19. A slightly different English translation of both Parts I and II, along with an Appendix, appeared under the same title in the *London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 5th series **43** (1897), 226–239.

[46]Zeeman, 'Light Radiation', *op. cit.*, note 31, p. 35.

was unable to see it. In fact, it was only just capable of detection by the means employed." (Emphasis added.)[47] Zeeman's attempt to isolate and stabilize the phenomenon named after him required remarkable observational skills, a fact which is not adequately conveyed by the mode of presentation of his experimental findings.

Nonetheless Zeeman's experiments were, in fact, reproduced.[48] In a historical review of Zeeman's discovery, Sir Oliver Lodge remarked that Larmor "wrote to me suggesting that I should examine and confirm the result. In a week I had done so, with such appliances as were to hand; though not without sufficient difficulty to make me . . . admire the skill of Zeeman in detecting the effect."[49] Larmor had realized the far-reaching implications of Zeeman's discovery with respect to the constitution of matter, and therefore wanted to establish the validity of the experiment.[50]

Before turning to the next, explicitly theory-guided, stage of Zeeman's experimentation, let us examine briefly two papers by the Belgian astronomer Ch. Fievez and their analysis by Zeeman. These papers,[51] which came to Zeeman's attention *only after* the original publication of his discovery,[52] contained descriptions of experiments similar to some of those performed by him. As noted earlier, Fievez's observations were in some cases incompatible with Zeeman's results. Understanding why is interesting and instructive for understanding the constitutive features of successful experimentation. Fievez, using a stronger field than Zeeman and exactly the same flame, observed not only a broadening of the lines but also their reversal and double reversal — "that is to say the appearance of a brilliant ray in the middle of the broadened dark ray".[53] In his analysis of Fievez's experimental findings, Zeeman tried to account for their discrepancy with his own results.[54] By employing Lorentz's theory he rejected the hypothesis that the more intense field was responsible for

[47]Lord Rayleigh, 'Pieter Zeeman (1865–1943)', *Obituary Notices of the Fellows of the Royal Society* **4** (1944), 590–595, on p. 592.

[48]The repetition of Zeeman's experiment was reported by Oliver Lodge in the Proceedings of the Royal Society. See, O. Lodge, 'The Influence of a Magnetic Field on Radiation Frequency', *Proceedings of the Royal Society of London* **60** (1897), 513–514.

[49]Oliver Lodge, 'The History of Zeeman's Discovery', *op. cit.*, note 44, p. 67. A similar remark is found in O. Lodge, *Electrons, or the Nature and Properties of Negative Electricity* (London: George Bell and Sons, 1906), p. 112.

[50]In Larmor's words, he "had been cognizant of the results of applying a magnetic field to the orbital ionic pair . . . Taking the masses of the ions to be comparable with that of a hydrogen atom, the spectral effect would be inappreciable. He pointed out the circumstance to Professor Lodge, and suggested the importance of confirming the experiment, which Lodge soon succeeded in doing." J. Larmor, *Mathematical and Physical Papers*, 2 vols (Cambridge: Cambridge University Press, 1929), Vol. 1, p. 140.

[51]Fievez, *op. cit.*, note 25.

[52]See P. Zeeman, *Communications from the Physical Laboratory at the University of Leiden* **36** (1897), Appendix to No. 33, 1–8, on p. 3.

[53]"c'est-à-dire l'apparition d'une raie brillante au milieu de la raie noire élargie". Fievez, "De l'influence", *op. cit.*, note 25, p. 384.

[54]See Zeeman, Appendix, *op. cit.*, note 52, p. 6.

Fievez's experimental outcome. Furthermore, he suggested that the phenomena observed by Fievez could "be attributed to a change of temperature by the well-known actions of the field upon the flame (change in its direction or outline, magnetic convection etc.)".[55] On the whole his main objection against Fievez's investigations was that they did not establish the direct action of magnetism on light. In other words, claimed Zeeman, Fievez did not eliminate perturbing factors which could be prevalent and distort the outcome of his experiments.[56]

And that brings me to the reasons for Zeeman's experimental success. As we have seen, qualitative speculations along with advanced technological resources (first and foremost the Rowland grating) were instrumental in his initial discovery. Moreover, the fact that he was not expert in current electromagnetic theories allowed him to proceed experimentally in investigations which, according to those theories, were doomed to failure. However, his discovery was much more than a combination of adequate technical facilities and theoretical clumsiness. The originality and ingenuity of his experiments consisted in the elaborate and sophisticated methods that he used in order to eliminate background 'noise' and thus establish the direct relationship between the observed effect and the action of magnetism. The change of the width of the spectral lines after the activation of the electromagnet was not by itself an indisputable demonstration of a direct interaction between magnetism and light. As we have seen, certain intermediate links, interposed between the generation of a magnetic field and its effect on the spectrum of a substance, could have explained the experiment's result and thus prevented Zeeman from postulating a direct causal connection between magnetism and light. Zeeman's significant achievement was in the elimination of all these potentially existing links.[57]

[55] *Ibid.*, p. 7.

[56] Zeeman's arguments show that J. Brookes Spencer's claim about "Fievez's painstaking establishment of a direct magnetic action upon spectral lines" is unjustified. Spencer, 'On the Varieties', *op. cit.*, note 13, p. 45. Oliver Lodge also endorsed Zeeman's dismissal of Fievez's results: "From the description [of Fievez's experiments], it appears likely that a variety of unimportant causes of disturbance must have been present, and that if the true effect was seen at all, it was so mixed up with spurious effects as to be unrecognisable in its simplicity, and so remained at that time essentially undiscovered". Lodge, 'The Latest Discovery', *op cit.*, note 43, p. 569. It should be noted that Preston did not share Zeeman's and Lodge's views: "Considering the unstable character of the sodium lines, I am strongly of opinion that M. Fievez was dealing with the real magnetic widening . . .". T. Preston, 'Radiation Phenomena in the Magnetic Field', *Philosophical Magazine* **45** (1898), 325–339, on p. 338. However, the important question was not whether Fievez was dealing with the real effect; it was rather whether Fievez *demonstrated* the existence of the real effect. The latter question was not addressed by Preston.

[57] Zeeman's achievement exemplifies one of Allan Franklin's 'epistemological strategies', which "entails the elimination of all plausible sources of error and all alternative explanations". This strategy is part of the "arguments designed to establish, or to help establish, the validity of an experimental result or observation". See A. Franklin, 'The Epistemology of Experiment', in D. Gooding *et al.* (eds), *The Uses of Experiment*, *op. cit.*, note 1, pp. 437–460, on p. 446 and p. 438 respectively.

4. For the Moment Theory Takes the Upper Hand

The next and final stage of Zeeman's discovery was dominated by Lorentz's electromagnetic theory of light.[58] That is why they were jointly awarded the Nobel Prize for Physics in 1902, "in recognition of the extraordinary service they rendered by their researches into the influence of magnetism upon radiation phenomena".[59] The first form of Lorentz's theory of the Zeeman effect is recorded in Zeeman's second paper on his celebrated discovery.[60] Zeeman initially thought that Lorentz's theory could provide an explanation of his experimental results.[61] Thus, he asked Lorentz to provide a quantitative treatment of the influence of magnetism on light:

> Prof. Lorentz to whom I communicated these considerations, at once kindly informed me of the manner, in which according to his theory the motion of an ion in a magnetic field is to be calculated, and pointed out to me that, if the explanation following from his theory was true, the edges of the lines of the spectrum ought to be circularly polarized. The amount of widening might then be used to determine the ratio of charge and mass to be attributed in this theory to a particle giving out the vibrations of light. *The above mentioned extremely remarkable conclusion of Prof. Lorentz relating to the state of polarization in the magnetically widened line, I have found to be fully confirmed by experiment.* [Emphasis added.][62]

Let us examine Lorentz's theoretical explanation of Zeeman's experimental findings in detail, as well as its heuristic impact on Zeeman's further investigations. According to Lorentz, the emission of light was a direct result of the vibrations of small electrically charged particles ('ions'), which exist in all material bodies. Aware that the configuration and movement of these 'ions' could be very complicated, Lorentz limited his explanation to the production of a single spectral line and, thus, the hypothesis that each atom contained a single 'ion' was adequately justified.[63] In the absence of a magnetic field the

[58]H. A. Lorentz, 'La théorie électromagnétique de Maxwell et son application aux corps mouvants', in P. Zeeman and A. D. Fokker (eds), *H. A. Lorentz, Collected Papers*, 9 vols (The Hague: Martinus Nijhoff, 1935–1939), Vol. 2, pp. 164–343. H. A. Lortenz, 'Versuch einer Theorie der electrischen und optischen Erscheinungen in bewegten Körpern', in *ibid.*, Vol. 5, pp. 1–137.

[59]*Nobel Lectures*, *op. cit.*, note 31, p. 10. The considerations which led to the decision to confer the award upon both Lorentz and Zeeman are discussed in Elisabeth Crawford, *The Beginnings of the Nobel Institution: The Science Prizes, 1901–1915* (Cambridge: Cambridge University Press, 1984), pp. 136–140.

[60]Zeeman, 'On the Influence of Magnetism (II)', *op. cit.*, note 45, pp. 12–16.

[61]This instance does not contradict my previous claim that Zeeman's discovery violated Lorentz's theoretical expectations. It only shows that Zeeman did not (and probably could not) employ the formalism of the theory in order to deduce its exact predictions with respect to the influence of magnetism on the motion of an 'ion'. It also shows that the abandonment of the tacit assumption that the radiating particles were as massive as hydrogen atoms would suffice for the accommodation of the new phenomenon.

[62]Zeeman, 'On the Influence of Magnetism (II)', *op. cit.*, note 45, p. 12.

[63]See also H. A. Lorentz, 'Ueber den Einfluss magnetischer Kräfte auf die Emission des Lichtes', *Wiedmannsche Annalen der Physik* **63** (1897), 278–284, on p. 278.

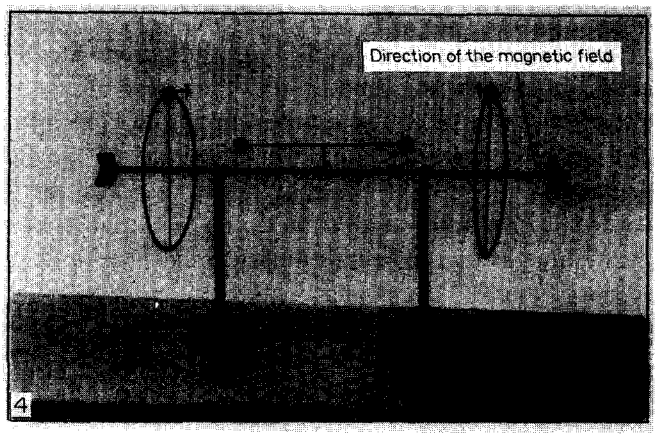

Fig. 4. "A model for the simple electronic motions".[64]

'ion' would oscillate about an equilibrium point under the action of an elastic force. The influence of a magnetic field would alter the mode of vibration of the 'ion'. Suppose that an 'ion' is moving in the xy-plane under the action of a uniform magnetic field which is parallel to the z-axis. The equations of motion are:

$$m\mathrm{d}^2x/\mathrm{d}t^2 = -k^2x + eH\mathrm{d}y/\mathrm{d}t$$
$$m\mathrm{d}^2y/\mathrm{d}t^2 = -k^2y - eH\mathrm{d}x/\mathrm{d}t$$

where e and m are the charge and the mass of the 'ion' respectively and H is the intensity of the magnetic field. The first term of the right side of the equations denotes the elastic force and the second term represents the force due to the magnetic field (the "Lorentz" force). The solution of this system of differential equation is:

$$x = ae^{st},\ y = be^{st} \text{ where } s \text{ is approximately } i(k/\sqrt{m})(1 \pm eH/2k\sqrt{m})$$

What is the physical significance of these solutions? In the general case, the oscillation of the 'ion' has an arbitrary direction in space. In the absence of a magnetic field the motion of the 'ion' can be resolved into three components:

[64]From Zeeman, *Researches*, *op. cit.*, note 30, p. 32.

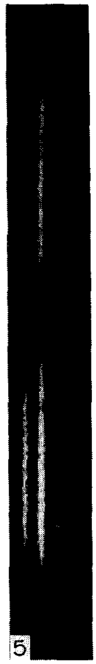

Fig 5. The splitting of the indigo line of cadmium into a triplet. From Preston, 'Radiation Phenomena', op. cit., *note 33.*

one linear oscillation and two circular oscillations perpendicular to the first. All three oscillations have the same frequency and the two circular ones have opposite directions (see Fig. 4). When a magnetic field is present, the oscillations along the direction of the field remain unaltered. But one of the circular components is accelerated, while the other is retarded. Further details of the theoretical analysis need not concern us here. What is important is that under the influence of magnetism the charged particle will yield three distinct frequencies. If the particle is observed along the direction of the field a doublet of lines will be seen. Each line represents circularly-polarized light. If it is observed in a direction perpendicular to the field, a triplet of lines will be seen. The middle component represents plane-polarized light, its plane of polarization being parallel to the field. The two outer components also represent plane-polarized light, but their plane of polarization is perpendicular to the field.

All these theoretical expectations were subsequently confirmed by experiments designed specifically to detect them. In the same paper that contained Lorentz's analysis Zeeman confirmed that the polarization of the edges of the broadened lines followed the theoretical predictions. Furthermore, from the observed widening of the spectral lines he estimated the order of magnitude of the ratio e/m (where e is the charge and m is the mass of the 'ion').[65] The splitting of lines was initially observed by Zeeman in 1897.[66] Instead of sodium he had used cadmium. Its indigo line was found to split into a doublet or triplet depending on whether the light was emitted in a direction parallel or perpendicular to the magnetic field (see Fig. 5).

This stage of Zeeman's experimentation was dominated completely by the theoretical insight of Lorentz.[67] Its principal aim was to test the validity of precise theoretical predictions. For the moment experiment became subservient to theory. Lorentz's theoretical anticipations led to new aspects of the novel phenomenon, which otherwise would have probably escaped Zeeman's attention. However, the refinement of the experiment soon led to theoretical advances. For instance, from the direction of polarization of the higher frequency component of the doublet Zeeman inferred that the charge of the 'ions' was negative.[68] Moreover, he gave a more accurate value of e/m and finally, by considering this unexpectedly large ratio, he was able to distinguish the 'ions' from the electrolytical ions.

Ultimately, though, experiment would again take the upper hand over Lorentzian theory, for the Zeeman effect turned out to be much more complicated than initially thought. As Lorentz remarked many years later:

> theory could not keep pace with experiment and the joy aroused by [Zeeman's] first success was but short-lived. In 1898 Cornu discovered — it was hardly credible at first! — that the line D1 is decomposed into a quartet and soon after considerably more complicated decompositions were observed. Theory in its turn, could,

[65]This was the first approximate measurement of e/m that indicated that the 'ions' corresponded to extremely minute subatomic particles. J. J. Thomson's measurement of the charge to mass ratio of the particles which constituted cathode rays was announced several months later and was in close agreement with Zeeman's result. See J. J. Thomson, 'Cathode Rays', *London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 5th series **44** (1897), 293–316. For an account of Thomson's 1897 experiments and a discussion of his debt to Zeeman see Isabel Falconer, 'Corpuscles, Electrons and Cathode Rays', *British Journal for the History of Science* **20** (1987), 241–276.

[66]P. Zeeman, 'Doublets and Triplets in the Spectrum produced by External Magnetic Forces', *London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 5th series **44** (1897), 55–60, 255–259.

[67]In view of my previous claim that Lorentz's theory precluded Zeeman's discovery it might seem paradoxical that the same theory guided the further refinement of the novel effect. However, the paradox disappears once it is pointed out that it was the conjunction of Lorentz's theory with the implicit assumption that the radiating particles were as massive as hydrogen ions that precluded the observation of the novel effect. As a result of Zeeman's discovery, this assumption was abandoned and Lorentz's theory of ions was subsequently transformed into his theory of electrons.

[68]It should be noted that Zeeman initially reported that these polarization results led to the conclusion that the 'ions' were positively charged. See Zeeman, 'On the Influence of Magnetism (Part II)', *op. cit.*, note 45, p. 18. However, he soon corrected his erroneous statement in his following paper. See Zeeman, 'Doublets and Triplets', *op. cit.*, note 66, p. 58. My attention was drawn to Zeeman's mistake by Shinji Endo and Sachie Saito, 'Zeeman Effect and the Theory of Electron of H. A. Lorentz', *Japanese Studies in History of Science* **6** (1967), 1–18. The same article contains (on pp. 5–6) a detailed account of several errors committed by Zeeman in his description of Lorentz's theoretical analysis of the novel phenomenon.

> however, only point to some extension of its first development to vibrating systems of arbitrary structure yet still governed by so-called "elastic" forces. Theory was however unable to account by this extension in any way for the regularities observed by various investigators to accompany the anomalous splitting of the lines belonging to the series of doublets and multiplets.[69]

This unexpected phenomenon, now called the 'anomalous Zeeman effect', includes any form of splitting that violated Lorentz's predictions. As the above passage indicates, Lorentz's theory proved unable to provide a satisfactory explanation of the more complicated patterns of magnetic splitting.[70] This was not a drawback peculiar to Lorentz's theory however, since the 'anomalous' Zeeman effect remained a problem for the 'old' quantum theory. As late as 1922, Arnold Sommerfeld remarked that "In its present state the quantum treatment of the Zeeman effect achieves just as much as Lorentz's theory, but no more. It can account for the normal triplet, including the conditions of polarisation, but hitherto it has not been able to explain the complicated Zeeman types".[71] An adequate explanation of the 'anomalous' phenomenon only became possible with the proposal of the spin concept by S. Goudsmit and G. E. Uhlenbeck in 1925.

5. Concluding Remarks

I have sought to examine various dimensions of experimentation by focussing on one experimental episode in the history of physics. As suggested at the outset, the analysis has implications for the ongoing philosophical debate over the relation between theory, observation, and experiment.

[69]H. A. Lorentz, 'De Theoretische Beteekenis van het Zeeman-effect', *Physica* **1** (1921), 228–241; translated as 'The Theoretical Significance of the Zeeman Effect' in *Collected Papers*, *op. cit.*, note 58, Vol. 7, pp. 87–100, on p. 90. In fact, Cornu was not the first to observe unexpected patterns of splitting. Thomas Preston had already announced on 22 December 1897 that, in the presence of a strong magnetic field, certain spectral lines of zinc and of cadmium split into four components. See Preston, 'Radiation Phenomena', *op. cit.*, note 33; and D. Weaire and S. O'Connor, 'Unfulfilled Renown: Thomas Preston (1860–1900) and the Anomalous Zeeman Effect', *Annals of Science* **44** (1987), 617–644. Lorentz's allusion to "more complicated decompositions" probably referred to the experimental results of C. Runge and F. Paschen, who observed in 1900 that the blue and green lines of mercury exhibit very complicated patterns of decomposition. See C. Runge and F. Paschen, 'Studium des Zeeman-Effektes im Quecksilber Spectrum', *Physikalische Zeitschrift* **1** (1900), 480–481.

[70]The severity of the problem posed by the anomalous Zeeman effect for Lorentz's theory is further illustrated by his remark in *The Theory of Electrons* (1909) that "we are rather at a loss as to the explanation of the complicated forms of the Zeeman effect". H. A. Lorentz, *The Theory of Electrons*, 2nd edn (Leipzig: B. G. Teubner, 1916), p. 130.

[71]A. Sommerfeld, *Atombau und Spektrallinien* (Braunschweig, 1922), p. 374; cited in J. Brookes Spencer, 'The Historical Basis for Interactions between the Bohr theory of the Atom and Investigations of the Zeeman Effect: 1913–1925', in *XII Congrès International d'Histoire des Sciences: Actes Tome V* (Paris: Blanchard, 1971), pp. 95–100, on pp. 95–96.

To begin with, there is little doubt that Zeeman's experiments were theory-laden. Therefore, "At issue should not be *whether* theory enters, but *where* it exerts its influence in the experimental process and *how* experimentalists use theory as part of their craft".[72] Zeeman was initially motivated by qualitative considerations about the effect of magnetism on light. Exploration of the specific features of this effect was the subject of the experimental work which culminated in his remarkable discovery. Background knowledge, both theoretical and experimental, played a central role in his researches. Theoretical constructs provided an understanding of the various instruments involved in the experimental process. For example, a precise knowledge of the operation and observational limits of the Rowland grating required the theoretical apparatus of wave optics.[73] On the other hand, experimental knowledge was crucial in distinguishing artefacts of the experimental apparatus from clues to nature's behaviour. We have seen, e.g., how Zeeman employed a phenomenon observed by Pringsheim in order to refine his light source and demonstrate the direct correlation between magnetism and light. Moreover, both experimental and theoretical, tacit and explicit, knowledge was required to delineate the domain of relevant parameters to the experiment's outcome. It was not accidental that Zeeman altered only a few of the parameters involved in his experiment.

Yet, despite the importance of theory for the experimental practices of Zeeman, there was a certain autonomy of his discovery from theoretical considerations. The search for what was subsequently called "the Zeeman effect" began with Faraday, who was motivated by speculative views on the unity of forces. In Zeeman's case the motivation was Kelvin's mechanical model of the ether and Faraday's authority as an experimentalist. In both cases the experiments were not performed in order to confirm or falsify precise theoretical predictions, but rather to explore a new territory, for which the above theories provided a rough heuristic guide. To a degree, Zeeman's experimentation had a life of its own which cannot be adequately understood as an offspring of pre-established theoretical anticipations. After the discovery, refinement and stabilization of the new effect, its autonomy was reinforced, since it became immune to changes in theoretical perspective. Theoretical developments in the study of atomic stucture did not challenge the existence of the phenomenon; instead, efforts were made to incorporate it into a viable picture of the physical world.[74]

[72]Galison, *Experiments*, *op. cit.*, note 1, p. 245.

[73]See Rowland, 'On Concave Gratings' *op. cit.*, note 31.

[74]The Zeeman effect is a nice "example of how experimental phenomena persist even while theories about them undergo revolutions". Ian Hacking, 'Experimentation and Scientific Realism', in Jarrett Leplin (ed.), *Scientific Realism* (Berkeley and Los Angeles: University of California Press, 1984), pp. 154–172, on p. 172.

The immunity of Zeeman's experiment to changes in theoretical perspective made it potentially capable of acting as an arbiter among competing theoretical views. Once the various details of the experimental discovery had been established, their significance was not theory-neutral. However, the theoretical and experimental reasons, through which the experiment's outcome came to be regarded as a manifestation of the direct interaction between magnetism and light, were independent from the theories under examination (in the first place Lorentz's theory of electromagnetic phenomena). In other words, one could believe in the significance and validity of Zeeman's experimental results *without* being committed to Lorentz's theory or, for that matter, to any other explanatory theory of the phenomenon. It was this independence that allowed the subsequent violation of theoretical expectations. Lorentz's theory, which played a decisive role in the elaboration and refinement of Zeeman's discovery, paradoxically, was falsified by the discovery of the 'anomalous' Zeeman effect, which was a straightforward experimental development of the classical case.

Finally, Zeeman's experimental work indicates that the role of background knowledge in experimental practice, along with the all-pervasive 'noise' render experimentation a much less straightforward procedure than has usually been assumed. It is the experimenter's task to employ background knowledge in order to eliminate the all pervasive 'noise', a task which requires a very subtle form of 'experimental' reasoning. The display of this reasoning in the narration of experimental discoveries amounts to the construction of an argument for the validity and significance of the reported experimental results. In Zeeman's case, his strategy in eliminating potentially distorting features of his experimental situation depended on already established experimental knowledge. The reasoning behind this strategy was displayed in the initial report of his discovery to persuade his audience that his experimental results revealed the direct influence of magnetism on light. Moreover, background knowledge, this time in the form of Lorentz's electromagnetic theory of light, guided further the experimental process and led to the discovery of additional aspects of the novel phenomenon. The refinement of the new effect led in turn to a crucial modification of Lorentz's theory, the distinction between his 'ions' and the ions of electrolysis. Thus, as the title of my paper indicates, the discovery of the Zeeman effect exemplifies the interplay between theory and experiment, a *sine qua non* of scientific practice.

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