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Pieter Zeeman - Nobel Lecture

Nobel Lecture, May 2, 1903

Light Radiation in a Magnetic Field

As Professor Lorentz told you last December, immediately after hearing of the great and very honourable distinction awarded to us, we set to work to see how best to co-ordinate our two lectures. To my great regret I was unable to be present here for Professor Lorentz's lecture, but he was able to report to you on present electron theory from his viewpoint, only briefly touching on the experimental investigations which have occupied me in recent years. I hope that you will allow me therefore to emphasize these experimental investigations. Two fields of physics, light and magnetism, are combined in the subject of today's lecture, whose history dates only from the days of Michael Faraday. The wonderful discovery of the connection between light and magnetism, which he made in 1845, was the reward for an investigation carried out with indefatigable patience and tenacity. Today we call this connection the magnetic rotation of the polarization plane. Faraday succeeded in showing that the plane in which light oscillations take place, is rotated as soon as light passes through special magnetizable bodies along the lines of force. Faraday himself called his discovery the magnetization of light and the illumination of magnetic lines of force. His contempories did not understand this name, which perhaps corresponded more to what he was searching for than to what he found. Throughout his life his hopes, desires and yearnings led him to make repeated investigations into the connection between light, magnetism, and electricity.

The last experiment recorded in Faraday's laboratory notebook and ostensibly the last in his life, gives an indication of the extent to which his spirit was still occupied with the boundary region of possible phenomena.

It was on March 12, 1862, in the laboratory of the Royal Institution that Faraday carried out this experiment. The notes in his notebook, although not quite clear, leave no doubt that he was attempting to demonstrate by means of a spectroscope that magnetism has a direct effect on a light source. The result was however absolutely negative, and Faraday writes in his notebook "not the slightest effect demonstrable either with polarized or unpolarized light".

Perhaps it was because of this observation that Maxwell, at a meeting of the British Association in Liverpool on September 15, 1870, said of the light-radiating particles in a flame "that no force in nature can alter even very slightly either their mass or their period of oscillation", a statement which, coming from the mouth of the founder of the electromagnetic light theory and spoken with such intensity, must really surprise present-day physicists.

It was not simply out of a spirit of contradiction that I exposed a light source to magnetic forces. The idea came to me during an investigation of the effect discovered by Kerr on light reflected by magnetic mirrors.

When it is a question of splitting up the light of a luminous gas into very fine detail, the simple glass prism of Newton and Frauenhofer is of no use, and the physicist has recourse to the excellent aid which we owe to Rowland: the concave grating. Most physics institutes possess this 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.

Of course the light source must be very restricted for the large number of beams corresponding to the various kinds of light to appear separately. This is ensured by placing the light source behind an opaque screen with a linear slit. The spectral image produced can be observed, and from the location and intensity of the linear-slit images we can determine how the different kinds of light in the light being studied are distributed on the basis of the period of oscillation and intensity. A further main advantage of Rowland's grating is that it is now no longer scratched on plane 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. Moreover, photography has made it possible to fix these images and now provides us with a permanent record of each observed spectrum, which can be measured out at any time.

When we study the well-known Bunsen sodium flame by means of Rowland's grating, we see a spectrum consisting mainly of two separate sharp yellow lines, which in our grating lie about I mm from each other. We see that sodium radiation consists of two kinds of light, the periods of oscillation of which differ only very slightly (1 in 1000) from each other. We confined our attention exclusively to one of these two lines.

I must ask you now to go with me into the Physics Institute of Leiden University. In August, 1896, I exposed the sodium flame to large magnetic forces by placing it between the poles of a strong electromagnet. Again I studied the radiation of the flame by means of Rowland's mirror, the observations being made in the direction perpendicular to the lines of force. Each line, which in the absence of the effect of the magnetic forces was very sharply defined, was now broadened. This indicated that not only the original oscillations, but also others with greater and again others with smaller periods of oscillation were being radiated by the flame. The change was however very small. In an easily produced magnetic field it corresponded to a thirtieth of the distance between the two sodium lines, say two tenths of an Angstrom, a unit of measure whose name will always recall to physicists the meritorious work done by the father of my esteemed colleague.

Had we really succeeded therefore in altering the period of vibration, which Maxwell, as I have just noted, held to be impossible? Or were there some disturbing circumstances from one or more factors which distorted the result? Several of such might be mentioned.

We doubted the result. We studied the light source in the direction of the magnetic force, we perforated the poles of the magnet; but even in the direction of the magnetic lines of force we found that our result was confirmed. We also studied the reverse phenomenon, the absorption of light in sodium vapour, and this too satisfied our expectations. We then asked, do different substances behave in different ways? What happens when the magnetic force is raised to the maximum attainable values? How do different lines of the same substance behave? But before these questions could be answered, theory took over.

I was in fact able to verify experimentally some conclusions which followed from the theory of optical and electrical phenomena of my esteemed teacher and friend Professor Lorentz. This theory assumes that all bodies contain small electrically charged mass particles, "electrons", and that all electrical and optical processes are based on the position and motion of these "electrons". Light oscillations result from the vibration of the "electrons". On the basis of Lorentz's theory, if we limit ourselves to a single spectral line, it suffices to assume that each atom (or molecule) contains a single moving electron.

Now if this electron is displaced from its equilibrium position, a force that is directly proportional to the displacement restores it like a pendulum to its position of rest. In this model the electrons are represented by the red balls and the direction of the magnetic force by the arrows. Now all oscillatory movements of such an electron can be conceived of as being split up into force, and two circular oscillations perpendicular to this direction rotating in opposite directions. In the absence of a magnetic field the period of all these oscillations is the same. But as soon as the electron is exposed to the effect of a magnetic field, its motion changes. According to well-known electrodynamic laws, an electron moving in a magnetic field is acted upon by a force which runs perpendicular to the direction of motion of the electron and to the direction of the magnetic field, and whose magnitude is easily determined. Here the rectilinear oscillation is not changed by the magnetic field, the period remains the same; on the other hand the two circular oscillations are subjected to new forces which, running parallel with the radius, either increase or decrease the original central force. In the first case the period of oscillation is reduced, in the second it is increased.

Now it is easy to determine the light motion to which this type of motion of the electrons will lead.

Let us consider first what happens in a direction running *perpendicular to the lines of force*. To the three electron motions there correspond three electrical oscillations, or in terms of the electromagnetic light theory three light oscillations of different periods. Thus the light source will emit *three*-colour light instead of the original *one*-colour light. Therefore, instead of the single non-polarized spectral line we shall see three separate lines when we place the light source in a magnetic field. The different directions of oscillation of the electrons affect the polarization state of the emitted light. The light of the middle component oscillates in parallel with, and that of the outer components perpendicular to the lines of force.

I will presently show you as an illustration a line which actually displays this behaviour postulated by Prof. Lorentz's theory.

But let us first consider the rays which run *parallel with the lines of force*. For this purpose I will rotate the model so that the arrow points in your direction. The opposite circular oscillations of the electrons excite two circularly polarized rays rotating in opposite directions, one having a longer and the other a shorter period of oscillation than the original spectral line. The original spectral line splits up under the action of the magnetic field into two components which are circularly polarized in opposite directions. The light source emits *two*-colour light.

I would now like to project for you two enlargements of photographs taken with the aid of Rowland's grating.* The lines are cadmium lines. In the first half of the picture you can see the unchanged line, and in the second rectilinear oscillations occurring in the direction of the magnetic lines of half the line changed by magnetic forces, the so-called triplet, which we see in the direction perpendicular to the lines of force.

Secondly I will project for you a cadmium line observed in the direction of the lines of force. The first half of the picture shows the unchanged line, and the second half the double line or doublet produced by the magnetic forces.

You see how beautifully the consequences following from Prof. Lorentz's theory were confirmed by observation in these cases. I should point out, however, that at first some difficulty was experienced in observing the phenomena predicted by the theory, owing to the extreme smallness of the variations in the period of oscillation.

I have just said that the change was extremely small; but it could be said that it was unexpectedly large. The magnetic cleavage of the spectral lines is dependent on the size of the charge of the electron, or, more accurately, on the ratio between the mass and the charge of the electron. Let us see what the observations teach us. When Prof. Lorentz published his theory in 1895, no data were available from which to estimate the ratio between the mass and the charge of the light-exciting particles, and in this theory the ratio was left undefined. We can now calculate this ratio from the magnitude of the magnetic splitting of the spectral lines: it is 10^7 c.g.s. units per gram, a colossal number even for the physicist, since it is 1,000 times as great as the similar number which was known from electrolysis phenomena in the case of hydrogen atoms. This makes it most probable for the physicist that in the luminous particles only ca. 1/1000th of the atom oscillates, and that the main mass of the atom remains virtually stationary. The oscillating electrons and the electrolysis ions were found to be not identical with each other; if they had been, the splitting of the spectral lines would have been only one thousandth of that observed, and then I should not have had the honour of addressing you in Stockholm today.

A further question must also be answered here and now, namely, are the oscillating particles positively or negatively charged?

We observed the doublet in the direction of the magnetic lines of force and studied the sign of the polarization. Then I suddenly resolved the problem: the oscillating electrons are *negatively* charged. We now know that cathode rays, which can occur in tubes filled with highly rarefied gases, are negative particles with the same high charge/mass ratio. We can conclude that that which vibrates in the light source is the same as that which travels in cathode rays.

We can hardly avoid recalling the two titles of Faraday's basic work: "Magnetization of light", "Illumination of lines of force" They appear to us to be almost prophesies, because we have now seen that light can in fact be magnetized, and according to Prof. Arrhenius's theory we have in nature itself, in the northern lights, an example of illumination of the magnetic lines of force of the Earth by the electrons escaping from the sun.

Nature gives us all, including Prof. Lorentz, surprises. It was very quickly found that there are many exceptions to the rule of splitting of the lines only into triplets. The French physicist Cornu was perhaps the first to observe that, contrary to the elementary theory, in some cases splitting into four lines, a quadruplet, occurs. In other cases splitting into five, six or even nine lines can be observed. In the line-rich spectrum of iron we find a whole selection of different forms. Very soon a number of physicists were working in the extended field; I need only name Becquerel, Cotton, Michelson, Preston, Righi, Runge, and Paschen. If I had more time at my disposal, I would gladly deal in greater detail with the work of the last-mentioned investigators. For the present, however, I must confine myself to projecting a cadmium line for you, which is split up into four lines, and negatives of a mercury line which has split up into nine components, and for which I am grateful to Prof. Runge. But despite this very complicated splitting-up, even when larger aids are used, the division into three groups of oscillations, two perpendicular to and one parallel with the lines of force, assumed in Lorentz's elementary theory, remains valid, as this photograph of the nonet shows.

It was natural that, soon after I had succeeded in splitting up lines, I should also study how the different lines behave in this respect. I was soon able to show by investigating the zinc lines that there are great differences in the splitting-up of different lines of a substance. Particularly great differences were found in lines belonging to different series, the discovery of which we owe to the lucid investigations of your countryman Prof. Rydberg, and in particular Professors Kayser and Runge.

I found very great differences in the lines of the different series, and it appeared that the splitting-up, contrary to the postulations of the elementary theory, expressed in the scale of oscillation frequencies, is *not* the same for all lines in the same magnetic field. We can conclude from this on the basis of Lorentz's theory that the charge/mass ratio is not the same for all electrons.

I would now like to talk about three separate phenomena, first a phenomenon which I have not been able to observe, secondly phenomena which I have hardly been able to verify, and thirdly a surprising phenomenon.

All the results which have been discussed so far have related to line spectra; but in the case of many bodies we also know of the existence of band spectra. Here a difference is found : the band spectrum displayed by iodine vapour or bromine vapour as an absorption medium at low temperatures, remains unchanged in a magnetic field; I personally have been unable to bring about any change in the extremely accurate images which Prof. Hasselberg has given us of the absorption spectra of bromine and iodine vapour, even with the strongest magnetic fields.

We are indebted to Prof. Voigt in Göttingen for a comprehensive theory of magneto-optical phenomena. The triplet you have seen today was absolutely symmetrical, as postulated in the elementary theory. Now on the basis of his theory Prof. Voigt was able to predict that as a result of the action of *weak* magnetic forces asymmetry should occur. According to him, the two external components should have different light intensities and be at different distances from the centre line. In the case of iron, zinc, and cadmium lines I was able to observe both asymmetries; because of their extreme smallness, however, I cannot demonstrate the phenomena in the projector.

However, another phenomenon, which will give you some idea of the scope of Voigt's theory, is more striking. In this phenomenon Faraday's magnetic rotation of the polarization plane and the magnetic splitting of the spectral lines, are intimately connected with each other.

The rotation of the polarization plane is extraordinarily small in all gases, thus also in sodium vapour. As Macaluso and Corbino found, it is only in the case of those colours which lie close to an absorption band of the vapour that the rotation is very great, of the order of 180°, and the rotation takes place in the *positive* direction, the direction of the current exciting the magnet.

What about the rotation inside the absorption band?

Prof. Voigt was able to predict that in the case of highly rarefied vapours the rotation must be negative in the zone between the two components of the doublet, i.e. opposite in direction to that outside the band, and also very great. I had the pleasure of confirming this theoretical finding in experiments on sodium vapour. Provided that the vapour is highly rarefied, the rotation in very strong fields between the lines of the doublet can rise to -400°.

To give you some idea of the distribution of the rotations, I will show you two negatives connected with this investigation.

The magnetic field is *not* set up.

The two dark vertical lines are the absorption lines of sodium vapour, the well-known D-lines. The reason why they are so broad is that the vapour was very dense. The horizontal bands are interference bands, which were produced by means of a special device. They indicate the points where the direction of oscillation is the same. The directions of oscillation in each of the successive bands differ by 180°.

Now as soon as the magnetic field is set up we get the image now being projected. On each side of each of the D-lines the bands bend *upwards*, the more so the smaller the distance, because the rotation in the vicinity of the bands grows very rapidly and reaches almost 180° in the immediate neighbourhood of the bands. Within the bands a blurred band only is visible.

The phenomenon becomes far clearer once the vapour is highly rarefied. The bands bounding the components *rise* as before. At the same time, however, the inner band becomes detached; it has *fallen*, the rotation is negative. In our third image the rotation in the case of one of the D-lines is about -90°, in the other everything is more blurred, the rotation is about -180°.

Summarizing briefly the results of the tests described in the light of Lorentz's theory, it can be stated that firm support has been found for the assertion that electricity occurs at thousands of points where we at most conjectured that it was present. Innumerable electrical particles oscillate in every flame and light source. We can in fact assume that every heat source is filled with electrons which will continue to oscillate ceaselessly and indefinitely.

All these electrons leave their impression on the emitted rays. We can hope that experimental study of the radiation phenomena, which are exposed to various influences, but in particular to the effect of magnetism, will provide us with useful data concerning a new field, that of atomistic astronomy, as Lodge called it, populated with atoms and electrons instead of planets and worlds.

I count myself fortunate to be able to contribute to this work; and the great interest which the Royal Swedish Academy of Sciences has shown in my work and the recognition that it has paid to my past successes, convince me that I am not on the wrong track.

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* A number of lantern slides were projected in the course of the lecture.