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A nineteenth-century discovery with enormous implications for the twenty-first century: a tribute to Zeeman's original paper in the *Philosophical Magazine*

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Attention is drawn to Zeeman's famous communication 'On the Influence of Magnetism on the Nature of the Light emitted by a Substance' in the *Philosophical Magazine* of 1897 by recalling his experiments and putting them in the context of present-day knowledge and use.

1. Introduction

Perhaps nowadays we can no longer envisage the fascination that (electro-) magnetism caused in the last decades of the nineteenth century. Oersted's discovery of the electromagnetic interaction in 1821 [1] (see also the wonderful discussion in [2]) spread amazingly fast over Europe and raised the curiosity of many scientists within only a few years. Quite a few famous effects that are now very familiar to us were the outcome of this curiosity and of attempts to understand all circumstances in which magnetism would play a 'mysterious' role. One of the findings discovered in this period of time was communicated in 1897 'to the readers of the *Philosophical Magazine*' by P. Zeeman [3] in an article entitled by 'On the Influence of Magnetism on the Nature of the Light emitted by a substance', see **Facsimile 1**. Starting off from some unsuccessful experiments by Faraday to investigate the effects of magnetism on the spectrum of a flame, Zeeman had the idea of considering a very particular set-up, namely to place a Bunsen burner between the poles of an electromagnet and to put 'a piece of asbestos impregnated with common salt in the flame in such a manner that the two D-lines were seen as narrow and sharply defined lines on the dark ground', see **Facsimile 2**. And: 'if the current was put on [i.e. the external magnetic field was switched on], the two D-lines were distinctly widened. If the current was cut off they returned to their original position.... The experiment could be repeated an indefinite number of times'. Clearly enough this must indeed have been a puzzling result. It was not caused by the gas used to operate the Bunsen burner, since 'the flame of the Bunsen was... interchanged with a flame of coal gas fed with oxygen' and the

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same phenomenon was recorded. Obviously it also was not just a specific feature of rock salt, as 'with the red lines of lithium, used as carbonate, wholly analogous phenomena were observed'.

Facsimile 1: The beginning of Zeeman's original publication.

Facsimile 2: Zeeman's experiment.

The conclusions, see **Facsimile 3**, he drew from his results were rather cautious: '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'.

Facsimile 3: Zeeman's conclusions.

Of course Zeeman could not give any coherent microscopic explanation of the phenomena he had discovered since not even Bohr's atomic model was around at his time. But, following the advice of Lorentz, he did discover another peculiar feature of his results, namely that the polarization state of the emitted light was also changed in the presence of an external magnetic field. 'The plate and the nicol were placed relatively in such a manner that right-handed circularly light was quenched. Now ... the widened line must at one edge be right handed circularly-polarized, at the other edge left-handed. By a rotation of the analyzer over 90° the light that was first extinguished will be transmitted and vice versa .... This experiment could be repeated any number of times'.

Zeeman's discoveries offered quite a few hints for later theories; however, for these to be formulated not only had the electronic spin to be discovered [4, 5], but also Schrödinger's wave mechanics [6] had to become relativistic [7–9]. Perhaps only in one aspect did Zeeman turn out to be wrong: he was too humble in communicating his results to 'the readers of the *Philosophical Magazine*' when he stated that 'possibly the observed phenomena will be regarded as nothing of any consequence', see **Facsimile 2**. Probably it was only the arrival of modern information technology and of nanoscience that proved the enormous importance of the phenomena discovered in 1897 which we now call the Zeeman effect. Some features of such uses will be briefly summarized in Section 5. However, before getting to this stage, a quantum mechanical interpretation of Zeeman's findings will be given, which – as already indicated – has to be based on a relativistic approach.

2. The Dirac operator for a central field

Let $\mathcal{H}_0$ be the (time-independent) Dirac Hamiltonian for a central field $V(|\vec{r}|)$

$$\mathcal{H}_0 = c\vec{\alpha} \cdot \vec{p} + \beta mc^2 + V(|\vec{r}|)I_4, \tag{1}$$

corresponding to the boundary conditions of an atom

$$\lim_{r \to 0} r^2 V(|\vec{r}|) = 0, \quad \lim_{r \to \infty} V(|\vec{r}|) = 0, \tag{2}$$

where I_n denotes an n-dimensional unit matrix. In equation (1) $\vec{\alpha}$ and β refer to Dirac matrices,

$$\vec{\alpha} = \begin{pmatrix} 0 & \vec{\sigma} \\ \vec{\sigma} & 0 \end{pmatrix}, \quad \beta = \begin{pmatrix} I_2 & 0 \\ 0 & -I_2 \end{pmatrix}, \tag{3}$$

$\vec{\sigma}$ being a formal vector consisting of the Pauli spin matrices σ_x, σ_y, and σ_z,

$$\vec{\sigma} = (\sigma_x, \sigma_y, \sigma_z), \tag{4}$$

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \tag{5}$$

Due to the block-diagonal structure of β, the wavefunctions $\psi^0(\vec{r})$ belonging to $\mathcal{H}_0$ are so-called bispinors,

$$\psi^0(\vec{r}) = \begin{pmatrix} \phi^0(\vec{r}) \\ \chi^0(\vec{r}) \end{pmatrix}. \tag{6}$$

For a central field, $\mathcal{H}_0$ has the following constants of motion

$$[\mathcal{H}_0, J^2]_- = [\mathcal{H}_0, J_z]_- = [\mathcal{H}_0, K]_- = 0, \quad K = \beta\left(\vec{\sigma} \cdot \vec{L} + 1\right), \tag{7}$$

that correspond to the well-known quantum numbers j, μ and κ in terms of the eigenvalue equations:

$$\begin{aligned} J^2\phi^0(\vec{r}) &= j(j+1)\phi^0(\vec{r}), & J^2\chi^0(\vec{r}) &= j(j+1)\chi^0(\vec{r}), \\ J_z\phi^0(\vec{r}) &= \mu\phi^0(\vec{r}), & J_z\chi^0(\vec{r}) &= \mu\chi^0(\vec{r}), \\ \left(\vec{\sigma} \cdot \vec{L} + 1\right)\phi^0(\vec{r}) &= -\kappa\phi^0(\vec{r}), & \left(\vec{\sigma} \cdot \vec{L} + 1\right)\chi^0(\vec{r}) &= \kappa\chi^0(\vec{r}). \end{aligned} \tag{8}$$

An eigenfunction of $\mathcal{H}_0$, J^2, J_z and K can therefore be written as

$$\psi^0_{\kappa\mu}(\vec{r}) = \begin{pmatrix} g_\kappa(r)\chi_{\kappa\mu}(\hat{r}) \\ if_\kappa(r)\chi_{-\kappa\mu}(\hat{r}) \end{pmatrix}, \tag{9}$$

and fulfils the property

$$\left\langle \psi^0_{\kappa\mu}(\vec{r}) \middle| \mathcal{H}_0 \middle| \psi^0_{\kappa'\mu'}(\vec{r}) \right\rangle = \int \psi^0_{\kappa\mu}(\vec{r})^* \mathcal{H}_0 \psi^0_{\kappa'\mu'}(\vec{r}) d\Omega = E^0_{\kappa\mu}\delta_{\kappa\kappa'}\delta_{\mu\mu'}, \tag{10}$$

$E^0_{\kappa\mu}$ being the $\kappa\mu$-th (one-electron) eigenvalue for which, because of the orthonormality of the spin spherical harmonics, the following condition applies

$$E^0_{\kappa\mu} = E^0_\kappa, \quad \forall\mu \in \{-j, -j+1, \ldots, j-1, j\}. \tag{11}$$

In equation (9) the radial functions $g_\kappa(r)$ and $f_\kappa(r)$ are usually termed the 'large' and 'small radial component' and the $\chi_{\kappa\mu}(\hat{r})$ are so-called spin spherical harmonics,

$$\chi_{\kappa\mu}(\hat{r}) = \sum_{s=\pm 1/2} C\left(\ell, j, \frac{1}{2} | \mu - s, s\right) Y_{\ell,\mu-s}(\hat{r})\Phi_s, \tag{12}$$

the $C(\ell, j, (1/2)|\mu - s, s)$ being the famous Clebsch–Gordan coefficients, and where the $Y_{\ell,\mu-s}(\hat{r})$ are spherical harmonics, and the Φ_s refer to the spin basis functions

$$\Phi_{1/2} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad \Phi_{-1/2} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}. \tag{13}$$

3. The 'anomalous' Zeeman effect

Suppose one now considers the presence of a homogeneous magnetic field $\vec{H}$. In this case the corresponding Dirac Hamiltonian is given by [10]:

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_1, \tag{14}$$

$$\mathcal{H}_1 = e\vec{\alpha} \cdot \vec{A} = -\frac{e}{2}\vec{\alpha} \cdot \vec{r} \times \vec{H}. \tag{15}$$

Choosing $\vec{H}$ to point along the z direction,

$$\vec{H} \| z : \mathcal{H}_1 = -\frac{e}{2}|\vec{H}|(\alpha_x y - \alpha_y x), \tag{16}$$

it is easy to see that the only (remaining) constant of motion of $\mathcal{H}$ is J_z,

$$[\mathcal{H}, J_z]_- = 0, \quad [\mathcal{H}, K]_- \neq 0, \quad [\mathcal{H}, J^2]_- \neq 0. \tag{17}$$

The matrix elements of $\mathcal{H}_1$ in the basis of the eigenfunctions of $\mathcal{H}_0$, see equations (9) and (10),

$$\langle \psi^0_{\kappa\mu}(\vec{r}) | \mathcal{H}_1 | \psi^0_{\kappa'\mu'}(\vec{r}) \rangle = -\frac{ie|\vec{H}|}{2} R_{\kappa\kappa'} A_{\kappa\kappa'}, \tag{18}$$

are of rather simple structure as they consist of an easily accessible radial integral,

$$R_{\kappa\kappa'} = \int_0^\infty r^3 (g_\kappa(r) f_{\kappa'}(r) + g_{\kappa'}(r) f_\kappa(r)) dr, \tag{19}$$

and an angular part, which can be evaluated analytically

$$A_{\kappa\kappa'} = \int \left(\chi_{\kappa\mu}(\hat{r}) [\vec{\sigma} \times \vec{r}] \chi_{-\kappa\mu}(\hat{r}) \right) d\hat{r}, \tag{20}$$

$$A_{kk} = \frac{4i\ell\mu}{4\ell^2 - 1}; \quad k = \ell,$$

$$A_{-k,-k} = -\frac{4i(\ell + 1)\mu}{(2\ell + 1)(2\ell + 3)}; \quad k = \ell + 1,$$

$$A_{k,-k} = i\frac{\left[(\ell + 1/2)^2 - \mu^2\right]^{1/2}}{2\ell + 1}; \quad k = \ell,$$

$$A_{-k,k} = i\frac{\left[(\ell + 3/2)^2 - \mu^2\right]^{1/2}}{2\ell + 3}; \quad k = \ell + 1.$$

Expanding a solution $\Psi(\vec{r})$ of the Dirac equation,

$$\mathcal{H}\Psi(\vec{r}) = E\Psi(\vec{r}), \tag{21}$$

in the basis of the eigenfunctions of $\mathcal{H}_0$

$$\Psi(\vec{r}) = \sum_{\kappa,\mu} c_{\kappa\mu}\psi^0_{\kappa\mu}(\vec{r}), \tag{22}$$

one immediately gets the following set of equations

$$\sum_{\kappa,\kappa'}\sum_{\mu,\mu'} c^*_{\kappa\mu}\left[\langle\psi^0_{\kappa\mu}(\vec{r})|\mathcal{H}|\psi^0_{\kappa'\mu'}(\vec{r})\rangle - E\delta_{\kappa\kappa'}\right]\delta_{\mu\mu'}c_{\kappa'\mu'} = 0,$$

$$\sum_{\kappa\mu} c^*_{\kappa\mu}\sum_{\kappa'}\left[\langle\psi^0_{\kappa\mu}(\vec{r})|\mathcal{H}_1|\psi^0_{\kappa'\mu}(\vec{r})\rangle - \underbrace{(E - E^0_\kappa)}_{E'_{\kappa\mu}}\delta_{\kappa\kappa'}\right]c_{\kappa'\mu} = 0, \tag{23}$$

$$\sum_{\kappa,\kappa'}\sum_{\mu} c^*_{\kappa\mu}\left[-\frac{ie|\vec{H}|}{2}R_{\kappa\kappa'}A_{\kappa\kappa'} - E'_{\kappa\mu}\delta_{\kappa\kappa'}\right]c_{\kappa'\mu} = 0. \tag{24}$$

From equation (23) or (24) one can see that $E'_{\kappa\mu}$ is indeed a 'splitting energy' corresponding to the $\kappa\mu$-th channel, which approaches zero as $|\vec{H}|$ goes to zero. Clearly enough, the actual values of $E'_{\kappa\mu}$ have to be evaluated by solving the secular problem in equation (24), in which, however, because of the properties of the angular integration parts $A_{\kappa\kappa'}$ in equation (20), the coupling of angular momenta (double sum over κ and κ') is restricted by the condition $j' - j = 0, \pm 1$.

In figure 1 the splitting of a p-like one-electron state in the presence of an external magnetic field is shown schematically. As can be seen at $|\vec{H}| = 0$, relativistically

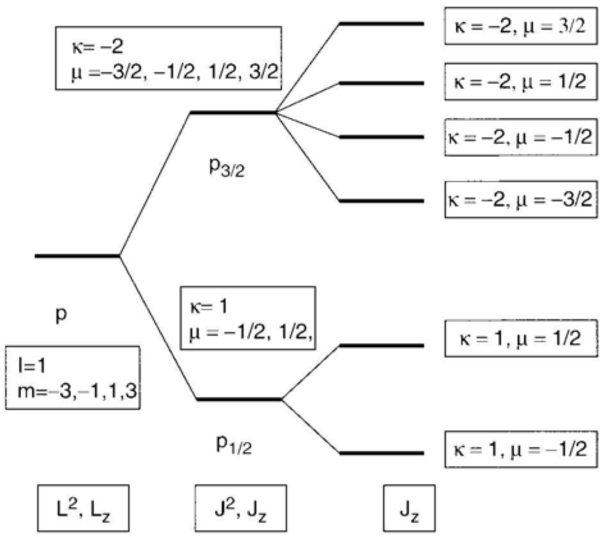

Figure 1. Schematic view of the Zeeman splitting: the corresponding quantum numbers and constants of motion are shown explicitly.

a non-relativistic p state splits into two levels, which in turn are split again in the presence of a magnetic field. Also shown in this figure are the corresponding constants of the motion.

It should be noted that a derivation of the Zeeman splitting can be given [10] also in terms of the Pauli–Schrödinger equation, i.e. in terms of an equation that contains relativistic effects up to c^{-2}, c being the speed of light. The important message, however, is that it needs at least the so-called 'spin–orbit' interaction to produce the splitting that Zeeman saw.

4. The Zeeman experiment: the Na emission line spectrum

Turning now to the experimental findings of Zeeman, namely the broadening of the Na D-lines, one has to invoke at least first-order time-dependent perturbation theory to handle the problem of emission spectroscopy. Assuming that – as usual – one can use an electric dipole approximation the transition probability per unit time is given by

$$P_{fi} = A_0^2\left(\frac{E_f - E_i}{\hbar}\right)^2 \left|\langle f|\vec{u}\cdot\vec{p}\,|i\rangle\right|^2 \delta(E_f - E_i + \hbar\omega), \tag{25}$$

where i and f denote the initial and the final state, respectively, A_0 is the (properly normalized) amplitude of the vector potential and $\vec{u}$ the (classical) polarization vector, which stands perpendicular to the propagation direction of light. Considering now, for matters of simplicity, only the Dirac delta-function in equation (25), the so-called energy conservation condition, from figure 1 one can see that in the presence of a magnetic field, even for a $\Delta j = 0$ transition four lines have to be observed experimentally. In general for a p to s transition the situation below applies,

	$\Delta j = 0$	$\Delta j = 1$
non-relativistic		$s \leftarrow p$
relativistic $\lvert\vec{H}\rvert = 0$	$s_{1/2} \leftarrow p_{1/2}$	$s_{1/2} \leftarrow p_{3/2}$
relativistic $\lvert\vec{H}\rvert \neq 0$	$s_{1/2}^{1/2} \leftarrow p_{1/2}^{1/2}, p_{1/2}^{-1/2}$	$s_{1/2}^{1/2} \leftarrow p_{3/2}^{1/2}, p_{3/2}^{-1/2}, p_{3/2}^{3/2}$
	$s_{1/2}^{-1/2} \leftarrow p_{1/2}^{-1/2}, p_{1/2}^{1/2}$	$s_{1/2}^{-1/2} \leftarrow p_{3/2}^{-1/2}, p_{3/2}^{1/2}, p_{3/2}^{-3/2}$

which clearly shows how confusing the so-called Zeeman splitting must have been for many years†.

Since in 1897 Zeeman's equipment was not sufficient to resolve the individual lines, he saw a broadening of the Na D-lines in the presence of a magnetic field, namely a superposition of naturally broadened lines of the transitions listed above, see figure 2.

His last observation concerning the different polarization state of the emitted light at the edges of the broadened Na D-lines is less easily explained, since this

†This is perhaps the reason why one still speaks about the 'anomalous' Zeeman effect, although there is no other Zeeman effect around.

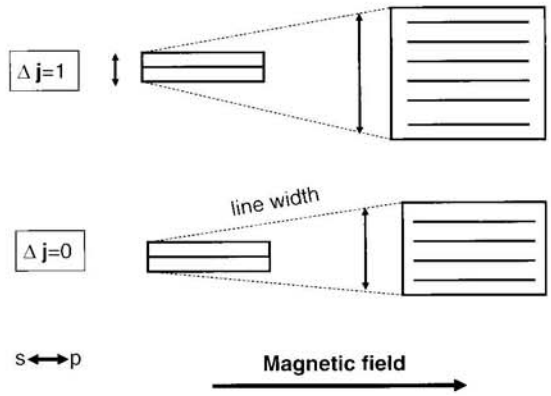

Figure 2. This is what Zeeman observed in the presence of an external magnetic field: the overlap of the natural linewidths due to the transitions from the $s_{1/2}^{\pm 1/2}$ to the $p_{3/2}^{\pm 1/2}$ and $p_{3/2}^{\pm 3/2}$ ($p_{1/2}^{\pm 1/2}$) levels.

requires evaluation of the selection rules that correspond to equation (25), i.e. the angular parts of $|\langle f | \vec{u} \cdot \vec{p} | i \rangle|^2$ for each particular transition.

5. The importance of the Zeeman effect

In order to appreciate the importance of Zeeman's findings in modern physics one might consider an effective one-electron Dirac Hamiltonian for a magnetic system such as that given by density functional theory [11–13]

$$\mathcal{H} = c\vec{\alpha} \cdot \vec{p} + \beta mc^2 + V(\vec{r})I_4 + \beta\vec{\Sigma} \cdot \vec{B}(\vec{r}), \tag{26}$$

where $V(\vec{r})$ is the effective potential and $\vec{B}(\vec{r})$ the effective exchange (magnetic) field,

$$V(\vec{r}) = V^{\text{eff}}[n, \vec{m}] = V^{\text{ext}} + V^{H} + \frac{\delta E_{xc}[n, \vec{m}]}{\delta n}, \tag{27}$$

$$\vec{B}(\vec{r}) = \vec{B}^{\text{eff}}[n, \vec{m}] = \vec{B}^{\text{ext}} + \frac{e\hbar}{2mc}\frac{\delta E_{xc}[n, \vec{m}]}{\delta \vec{m}}, \tag{28}$$

and $\vec{\Sigma}$ is the so-called spin operator,

$$\vec{\Sigma} = \begin{pmatrix} \vec{\sigma} & 0 \\ 0 & \vec{\sigma} \end{pmatrix}. \tag{29}$$

In equations (27) and (28) n is the particle density, $\vec{m}$ the magnetization density, $E_{xc}[n, \vec{m}]$ the exchange correlation energy, V^{H} the Hartree potential and V^{ext} and $\vec{B}^{\text{ext}}$ are external fields.

In figure 3 different levels of theoretical description are displayed for the (single-site) d-like resonances of Rh and Ir monolayers on Ag(001). In this figure, panel (a) refers to the non-relativistic spin-polarized case, and shows an exchange splitting that

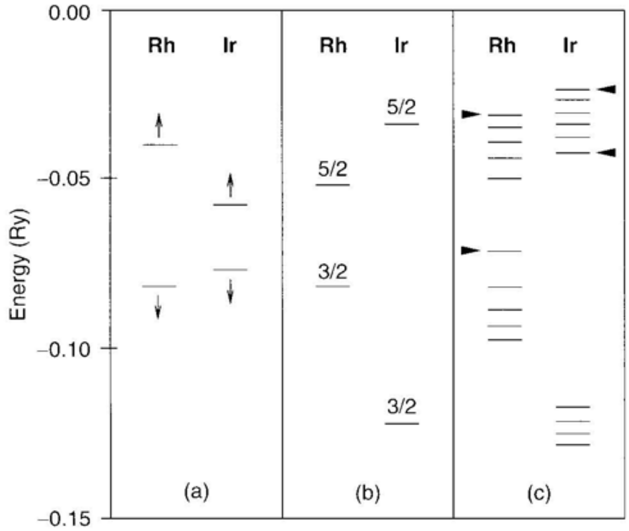

Figure 3. Calculated positions of d-like resonances of an Rh and an Ir overlayer on Ag(100). Panel (a) refers to the non-relativistic spin-polarized case, where the spin-up and spin-down channels are denoted by up and down arrows. The relativistic non-magnetic case is shown in panel (b) illustrating the spin orbit splitting between the $j = 3/2$ and $j = 5/2$ resonances. The relativistic spin-polarized case, see equation (26), is displayed in panel (c). The uncoupled resonances corresponding to $(j, \mu) = (5/2, -5/2)$ (upper ones) and $(5/2, 5/2)$ (lower ones) are indicated by small horizontal arrows. From [15].

is approximately twice as large for Rh as for Ir. In panel (b) the resonance energies corresponding to a fully relativistic non-magnetic approach are shown. Quite clearly, the spin orbit splitting of Ir, i.e. the splitting between the $d^{3/2}$ and $d^{5/2}$ resonance energy, is about three times larger than that of Rh. As compared to panel (a), the spin–orbit splitting of Rh amounts to only about 70% of the corresponding exchange splitting, while the spin–orbit splitting of Ir is more than four times larger than the corresponding exchange splitting. The fully relativistic spin-polarized case, namely the one corresponding to equation (26), is shown in panel (c). Here, Rh represents the 'strong magnetic case', in which the scattering channels corresponding to different j but to the same μ, namely $-3/2 \le \mu \le 3/2$ and $j = 3/2, 5/2$, are strongly coupled, while the two uncoupled resonances, $(j, \mu) = (5/2, -5/2)$, $(5/2, 5/2)$ are energetically separated approximately by the exchange splitting as shown in panel (a). For Rh this coupling obviously leads to an 'upper' and a 'lower' set of resonances, each of them consisting of five levels. In the case of Ir, the small exchange coupling results in an almost 'classical' Zeeman-type splitting of the $d^{3/2}$ and $d^{5/2}$ levels. Here the levels corresponding to the same j but to the opposite μ, like e.g. $(3/2, -3/2)$ and $(1/2, -1/2)$, are split only very weakly. For matter of completeness it has to be added that a single layer of Rh on Ag(100) carries a magnetic moment of 0.93 μ_B. For an Ir overlayer on Ag(100) only a non-relativistic calculation predicts a magnetic moment of 0.42 μ_B, while an evaluation in terms of equation (26) yields a non-magnetic system. For further details, see also [14].

5.1. *Magnetic anisotropies in bulk systems*

Suppose that in a magnetic bulk system such as fcc Ni $\vec{B}(\vec{r})$ in equation (26) is assumed to be parallel to either $\vec{n}_1$ or $\vec{n}_2$ (e.g. crystal axes), $|\vec{n}_i| = 1$. Then in general the difference in total energies corresponding to these two directions is non-vanishing

$$E(\vec{n}_2) - E(\vec{n}_1) \neq 0, \tag{30}$$

and the ground state of the system refers to the condition

$$E_0 = \min_{\vec{n}_i} E(\vec{n}_i). \tag{31}$$

Including the difference in the magnetic dipole–dipole interaction energy $E_{dd}(\vec{n}_i)$ semiclassically [14], which is not accounted for in equation (26), the difference

$$E_a = E(\vec{n}_2) - E(\vec{n}_1) + E_{dd}(\vec{n}_2) - E_{dd}(\vec{n}_1), \tag{32}$$

is the so-called magnetic anisotropy energy, which is usually quoted for $\vec{n}_1$ and $\vec{n}_2$ pointing along Cartesian unit vectors. Since in bulk systems E_a is only of the order of a few μeV, a proper inclusion of all effects, i.e. also of the Zeeman effect, see figure 3, is rather important.

5.2. *Layered systems, magnetic films, spin valves*

Consider now a layered system such as a spin valve system or a system with a surface and/or interfaces. Denoting the orientation of $\vec{B}(\vec{r})$ in the individual atom layers by $\vec{n}_i$, then for such a system $\vec{B}(\vec{r})$ in equation (26) is characterized by the following set of individual orientations

$$\vec{N} = \{\vec{n}_b, \vec{n}_1, \vec{n}_2, \vec{n}_3, \ldots, \vec{n}_N, \vec{n}_b\}, \tag{33}$$

where $\vec{n}_b$ for example refers to the orientation of the magnetization in the leads of a spin valve (GMR device). Magnetic anisotropy energies can then be defined in a similar manner as in equation (32), namely by

$$E_a = E(\vec{N}') - E(\vec{N}) + E_{dd}(\vec{N}') - E_{dd}(\vec{N}). \tag{34}$$

Preferred orientations of $\vec{B}(\vec{r})$ can change when modulating the thickness parameters of a system, by applying an external magnetic field, or by running an electric current perpendicularly through the planes of atoms. These three aspects are in essence the main tools in 'spintronics', which is now the backbone of modern information technology or will become so. As an example, in figure 4 the famous reorientation transition of Fe on Au(100) is shown. In this system the orientation of the magnetization is perpendicular to the planes of atoms up to three or four monolayers of Fe; for thicker Fe films (more than four Fe layers) it is in-plane. This example was chosen deliberately, since the Kerr effect applied to obtain the experimental data in figure 4 is *the* underlying physical effect used for magneto-optically reading.

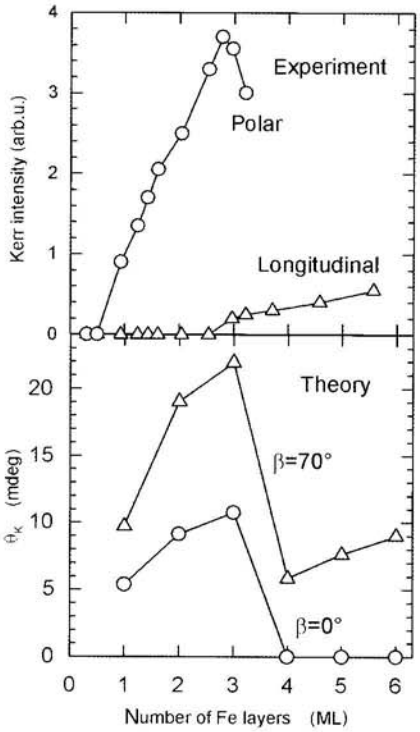

Figure 4. Top: SMOKE experiments by Liu and Bader [17]. Circles denote the measured data for the polar, and triangles for the longitudinal Kerr set-up. Bottom: calculated values of the Kerr rotation angle θ_K in the case of p-polarized incident light and for the magnetic ground state of Fe_n/Au(100). Circles mark the theoretical results for a normal incidence ($\beta = 0°$) and triangles for an incidence of $\beta = 70°$. From [16].

6. Conclusions

What was reported in 1897 by Zeeman as a mysterious line broadening of the Na D-lines in the presence of an external magnetic field, took almost 30 years to be explained on a microscopical level. A hundred years later, the Zeeman effect became one of the important ingredients of modern information technology. The Zeeman splitting is indeed important for electric transport in magnetic nanostructures; see the schematic view in figure 5, and for magneto-optical recording, see figure 6, since very often, as figure 3 shows, only the combination of exchange splitting and Zeeman splitting determines the underlying magnetic properties of a system.

Perhaps two more comments should be added with respect to the famous paper by Zeeman in the *Philosophical Magazine*. The footnote in the title line of the article 'Communicated by Prof. Oliver Lodge, FRS, with the remark that he had verified the author's results so far as related emission spectra and their polarization', see **Facsimile 1**, seems to indicate that in 1897 it was still possible for a referee, if not mandatory, to repeat an experiment to be reported and check the results obtained.

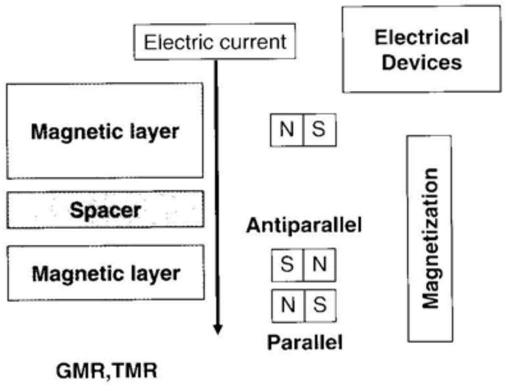

Figure 5. Schematic principle of GMR (Giant Magnetoresistance) and TMR (Tunnelling Magnetoresistance) devices. In the case of GMR the current is usually driven parallel to the planes of atoms. From http://www.cms.tuwien.ac.at/Nanoscience/nanoscience.html

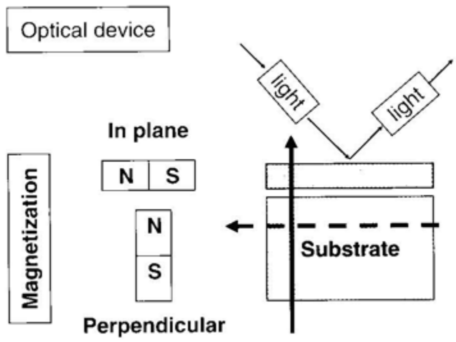

Figure 6. Schematic principle of a magneto-optical reading device (CD reading drive). From http://www.cms.tuwien.ac.at/Nanoscience/nanoscience.html

Nowadays this is virtually impossible, not only because of the huge number of papers that appear every year, but also since very often certain equipment is unique. Most important, however, we, the *posteriori*, should be reminded that perhaps occasionally a more critical self-assessment of our own scientific findings appears to be appropriate. It does not need to be always as humble as Zeeman's self-critical standpoint of view: 'Possibly the observed phenomenon will be regarded as nothing of any consequence', see **Facsimile 2**.

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