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The Action of a Magnetic Field on Light and Matter: Possible Direct Interaction between Magnetism and Light

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Abstract

Michael Faraday discovered that linearly polarized light could be rotated by a magnetic field as it propagated through a piece of "heavy glass." Since the effect could not be observed in air, Faraday assumed that the magnetic field acted on the glass and that the glass influenced the magnetic properties of light itself. According to the standard theory, the magnetic field causes the glass, which has a single refractive index in the absence of a magnetic field, to become optically active as a result of the Lorentz force acting on the electrons in the glass. As a result, the glass develops one refractive index for right circularly polarized (RCP) light and another refractive index for left circularly polarized (LCP) light. This results in the rotation of the azimuth of polarization. While the discovery of the Faraday effect was important evidence for the electromagnetic theory of light, the magnetic property of light itself that responds to the changes in the refractive index remains enigmatic.

Here we suggest that if light be described as being composed of equal and opposite moving charges within each binary photon, the magnetic field would act both on the glass and on the light itself. The binary photon model proposes that the photon is not an elementary particle but a complex of two particles that are conjugate in terms of mass, electric charge, and sense of rotation, whose movements generate a linearly polarized transverse electric field and a circularly polarized magnetic field that is orthogonal to the electric field and phase shifted by one quarter wavelength. The binary photon contains an electric dipole and a magnetic moment, which logically seem to be a *sine qua non* for the carrier of the electromagnetic force. As a result of the electromagnetic properties of the binary photon, the force exerted on the binary photons by the applied magnetic field used to demonstrate the Faraday effect would result in the transformation of binary photons with a single wavelength into binary photons with two different wavelengths. The binary photons with two different wavelengths would no longer experience the same refractive index as they propagated through the glass because by necessity, the glass required to show the Faraday effect with a relatively short geometrical path length must have high dispersion and a low Abbe number. As a result of the high dispersion and low Abbe number, the transformed binary photons with the shorter wavelength would experience a higher refractive index and the transformed binary photons with the longer wavelength would experience a lower refractive index. Consequently, as they propagated through the glass, the shorter wavelength binary photons would be retarded relative to the longer wavelength binary photons and the azimuth of polarization would be rotated. The model of the binary photon and its response to a magnetic field describes and explains the magnetic properties of light proposed by Faraday and the requirement for high dispersion glass to observe the Faraday effect. In addition, the electromagnetic properties of the binary photon have the required number of degrees of freedom to account for other magneto-optical phenomena such as the Zeeman effect.

There is a crack in everything. That's how the light gets in. From *Anthem* by Leonard Cohen

1. Introduction

The Athenaeum [1] announced on November 8, 1845 in its Weekly Gossip section that Michael Faraday had just discovered that "*a beam of polarized light is deflected by the electric current, so that it may be made to rotate between the poles of a magnet*." It went on to report that "*Light, the subtile agent of vision, the source of all the beauty of colour, is now shown to have some close relation with electricity, to which has long been referred many of the vital functions. As life and organization exist only where there is light, this discovery of Mr. Faraday's would appear to advance us towards some knowledge of those physiological phenomena which are the most recondite subjects of science*."

Faraday recorded in his diary on September 13, 1845 that he had tested the effect of electromagnetism on the passage of linearly polarized light through transparent substances, including air, flint glass, rock crystal, and calcareous spar placed between crossed polars, but found no effect [2]. However, when he used "heavy glass," consisting of a silicated borate of lead, he saw the flame of the Argand oil lamp appear when he turned on the current to the electromagnet. He saw that "*when the polarized ray passes parallel to the lines of magnetic induction, or rather to the direction of the magnetic curves, that the glass manifests its*

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[*] Michael Faraday's second cousin, seven times removed.

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power of affecting the ray. So that the heavy glass in its magnetized state corresponds to the cube of Rock crystal; the direction of the magnetic curves in the piece of glass corresponding to the direction of the optic axis in the crystal." He wanted to use a more powerful magnet.

On September 18, 1845, Faraday received and used the more powerful Woolrich electromagnet and clearly saw the image of the oil lamp when he turned on the current through the electromagnet. Moreover, he also found that upon turning on the current, the brightness of the image of the flame rose gradually just as the magnetic lines of force rise gradually. He then found that "*the new quality of force impressed on the heavy glass by the Magnetic curves is a circular polarizing force—for when without the Magnetic curves, the Nicholl eye piece is in that position which extinguishes the polarized ray—and when by inducing the Magnetic curves and peculiar state the image becomes visible, then revolving the Eye piece a certain quantity extinguishes the image. On taking off the magnetic influence an image again appears, and to put this out the Eye piece has to be revolved back to its first position*."

"*Further observed that when the Magnetic influence was exerted on the heavy glass, and the Eye piece so far revolved as to extinguish the image, that then further motion in one direction…in bringing into sight an image, gave it of a red colour—and on the contrary, that on revolving the eye piece in the other direction… produced an image, but of a blue or complementary colour. Are not these the properties of the circular polarization of quartz…?*"

Faraday [2] summed up his research by writing, "*I believe that, in the experiments I describe in the paper, light has been magnetically affected, i. e. that that which is magnetic in the forces of matter have been affected, and in turn has affected that which is truly magnetic in the force of light*."

On March 12, 1862, Michael Faraday performed his last experiment, which showed no effect of a magnetic field on the wavelength of light produced by salt in a flame placed between the two poles of an electromagnetic. Faraday [3] wrote, "*The colourless Gas flame ascended between the poles of the Magnet and the salts of Sodium, Lithium, etc. were used to give colour. A Nicol's polarizer was placed just before the intense magnetic field and an analizer at the other extreme of the apparatus. Then the E. Magnet was made and unmade, but not the slightest trace of effect on or change of the lines in the spectrum were observed in any position of the Polarizer or analyzer.*"

"*Two other pierced poles were adjusted at the magnet—the coloured flame established between them, and only that ray taken up by the optic apparatus which came to it along the axis of the poles, i.e. in the magnetic axis or line of magnetic force. Then the Electro Magnet was excited and rendered neutral; but not the slightest effect on the polarized or unpolarized ray was observed*."

While Faraday [4,5] was unable to detect any effect of the magnetic field on the wavelength of the light, Pieter Zeeman [6-9] and Thomas Preston [10,11] were able to do so. Zeeman showed that a magnetic field split one line in the sodium spectrum into a triplet, where the distance between the three lines depended on the strength of the magnetic field. Hendrik Lorentz [12] described a mechanism whereby the magnetic field produced a force on the electrons of sodium that that would account for the Zeeman effect. The Lorentz force would also result in the Faraday effect if it worked the same way on the electrons in the atoms that made up the "heavy glass."

For the past century, light has been considered to be composed of geometrical point-like photons that are electrically neutral and nonmagnetic [13,14]. Even though light is a carrier of electromagnetic force, a magnetic field could not act directly on light if the photons that composed the light were truly electrically neutral and nonmagnetic.

Recently, Wayne [15-19] has described light as being composed of binary photons that have two component parts known as semiphotons. The two components are conjugate to each other in terms of mass, electric charge, and sense of rotation. They oscillate and rotate in such a way as to generate an electromagnetic wave that exhibits wave-like behavior, including diffraction and interference [15,18]. The model of the binary photon is supported by its ability to explain the deflection of starlight [14].

The binary photon itself is both electric and magnetic [15,17]. The time-varying position of the charges give rise to a linearly-polarized electric field and the time-varying velocity with respect to the axis of electrical polarization gives rise to a circularly-polarized magnetic field that is orthogonal to and a quarter wavelength out-of-phase with the electric field. If there is something truly magnetic in the force of light, as Faraday assumed, is it possible that magnetic lines of force could act directly on light itself if light were to be composed of binary photons?

Wayne [14] has proposed that formally there may be four classes of binary photons that can be distinguished by the sign of the charge and sense of rotation (parity) of the leading and following semiphotons in each class. We decided to repeat Faraday's experiments to test the possibility that the magnetic lines of force could directly influence light itself in addition to influencing the electrons in the "heavy glass" through which the light propagates.

2. Materials and Methods

The experimental apparatus (Fig. 1) is composed of multiple laser pointers with various wavelengths, a rotatable polarizing filter (model #52574; Edmund Optics, Barrington, NJ, USA), a solenoid that is 15 cm long made from 10 layers of #18 double-insulated magnet wire (model 18H200P; Remington Industries, Johnsburg, IL, USA) wound 113 turns per layer, for a total of 1135 turns, a rod-shaped dielectric that is placed within the solenoid, a rotatable analyzer (model #52574; Edmund Optics, Barrington, NJ, USA), and a quantum/radiometer/photometer (model LI-189; LI-COR, Inc, Lincoln, NB, USA) with a pyrometer sensor (model LI-200SA; LI-COR, Inc, Lincoln, NB, USA). The dielectric was composed of a 5 mm x 100 mm rod of "heavy glass" (SF-57; TeachSpin, Buffalo, NY, USA). The "heavy glass" rod was not completely isotropic, but had small amount of strain birefringence that allowed some light to pass the crossed polars. All experiments were performed in the dark with the aid of a penlight.

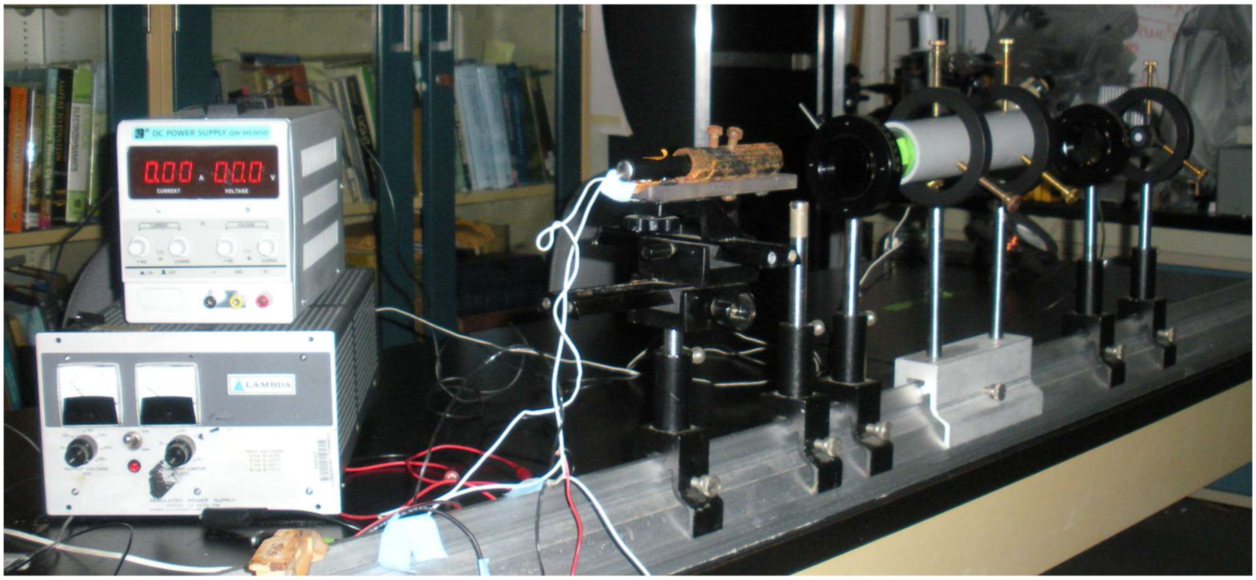


Fig. 1: A photograph of the apparatus used to investigate Faraday rotation. In the typical configuration, the North pole of the magnetic field is on the laser side of the electromagnet and the South pole is on the sensor side. Consequently, the light propagates from the North pole to the South pole in the solenoid antiparallel to the magnetic field lines.

The solenoid was powered by a power supply (model LK 343A FM; Lambda Electronics Corp., Melville, NY, USA and model QW-MS305D; Wuxi Quiowei Electronics, China) running in the constant current mode. The magnetic flux density (B) was calculated using the infinite uniform field approximation with the following equation ($B = \mu_o \frac{NI}{L}$), where $\mu_o = 4\pi \times 10^{-7}$ H/m, N is the number of turns (1135), I is the current and L is the length of the solenoid (1.6×10^{-1} m) or 8.9 mT per amp. The actual magnetic flux density was measured with a Hall effect magnetic field sensor (model MG-BTA; Vernier Software & Technology, Beaverton, OR) connected to a Dell Latitude laptop computer (Model E6430s) through a LabPro interface (Vernier Software & Technology, Beaverton, OR). The actual ratio of the magnetic flux density (milli Tesla) to the current (amperes) flowing through the electromagnet was 10.127 ± 0.032 mT/A ($\bar{x} \pm$S. D. ($n = 10$).

The laser was aligned so that the emitted light was directed through the "heavy glass" rod in the solenoid when no current was passing through it. The light emitted from the lasers is polarized, partially polarized or unpolarized, depending on the laser. In order to maximize the intensity of the light passing through the solenoid, the rotating polarizer was oriented so that it passed the maximal intensity of laser light. The rotating analyzer was then oriented 90° relative to the polarizer so that the light from the laser was maximally extinguished before it reached the pyrometer sensor. Maximal extinction ($\theta_{initial}$) was achieved when the output of the quantum/radiometer/photometer was minimal. The current to the solenoid was then turned on to generate a magnetic field. The rotating analyzer was set for $\pm 45°$ to determine the effect of the magnetic flux density on the intensity of light. When determining the effect of the magnetic flux density on the rotation of the linearly polarized light, the analyzer was rotated from -90° to +90°.

The lasers used included, a 5 mW 445 nm Blue Ray Portable Laser Pointer (Laserlands, China); a 5 mW 405 nm Violet-Purple Laser Pointer (TMART, China); a 5 mW 532 nm Green Laser Pointer (TMART, China); a 650 nm Red Laser Pointer (TMART, China); a 5 mW 635-638 Orange Red Laser Pointer (Besram-Tech, China); and a 5 mW 532 nm Green Laser Pointer with infrared filter (Laser-Tec, Fort Pierce, FL, USA). In order to include as many wavelengths as we could in this experiment, we watched the prices of laser pointers online. As the price of a laser pointers of a given wavelength fell below \$20, we bought it. The next laser pointer to fall below \$20 will probably be a yellow laser with a wavelength of 589 nm. It is currently over \$300.

Unlike the 405 nm, 445 nm, 636 nm and 650 nm lasers, which use laser diodes to produce monochromatic light directly, green lasers produce 532 nm light indirectly by pumping 808 nm infrared light, which is produced by a laser diode, through a neodymium-containing crystal, which lases at 1064 nm due to an electronic transition in the neodymium ions. The neodymium-containing crystal, which is mounted on a heat sink, is coated on the diode side with a dichroic mirror that reflects 808 nm light and transmits 1064 nm light. A second crystal, which is also mounted on the heat sink, is made of potassium titanyl phosphate. This crystal doubles the frequency or halves the wavelength of 1064 nm light to produce 532 nm green light. The light then passes through a dichroic mirror that reflects 1064 nm and transmits 532 nm light. The Laser-Tec green laser has an additional infrared filter that for safety's sake blocks the output of infrared light [20]. However, as a consequence of restricting the output of infrared light, the infrared light stays within the resonant cavity so that the laser heats up and becomes unstable when it is on for longer than is required in normal use as a pointer.

The polars are largely transparent to infrared light. In the 532 nm green laser without the infrared filter, the infrared light contributes the majority of the laser output power so that when the polars are crossed, the intensity is still about 97% of maximum. A solution of $CuSO_4$ is often used by plant physiologists to remove unwanted infrared light [21,22] and was used here to remove the unwanted infrared from the 532 nm green laser.

The infrared light produced by the green laser was removed by passing the light through a 5% (w/v) solution of $CuSO_4$ in a semimicro disposable cuvette (model 223-9950; Bio-Rad Laboratories, Hercules, CA, USA) with a path length of 1 cm. The cuvette was placed between the laser and the polarizer. However, the infrared light produced by the laser heated the laser itself and its intensity became unstable. This happened even more dramatically with the 532 nm laser that included the infrared filter. The intensity of the 532 nm laser without the infrared filter could be partially stabilized by surrounding the laser with a one gallon double lock freezer bag (Glad Products, Oakland, CA, USA), containing ice mixed with a saturated solution of NaCl.

The data were analyzed using an algorithm written in Mathematica that performs a nonlinear fit using a $\sin^2$ function. The program estimates three parameters: the maximum (a), the minimum (c), and the offset (b) using the formula: relative intensity = $c + a\sin^2(\theta + b)$. The program subtracts the minimum from each value in order to remove the portion of the signal that results from the partial depolarization of light caused by the strain in the glass.

3. Results and Discussion

In the absence of a current (i) running through the solenoid of the electromagnet, the laser light is extinguished by crossed polars. As the current through the solenoid is increased, the magnetic flux density along the axis of propagation increases and the light intensity that passes through the crossed polars increases in a nonlinear manner (Fig. 2).

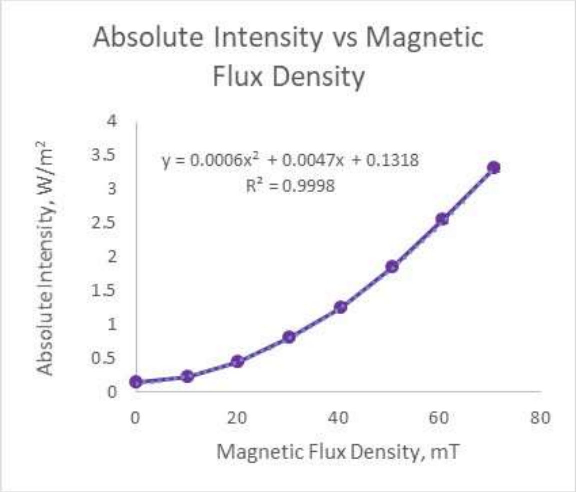


Fig. 2: The relationship between the magnetic flux density produced by the solenoid and the intensity of 405 nm light that passes through the crossed polars.

When the second polar is at an angle ±45° relative to the first polar, the light intensity either increases or decreases as the current through the solenoid increases and the magnetic flux density along the axis of propagation increases. In these cases, the absolute intensity depends linearly on the magnetic flux density (Fig. 3).

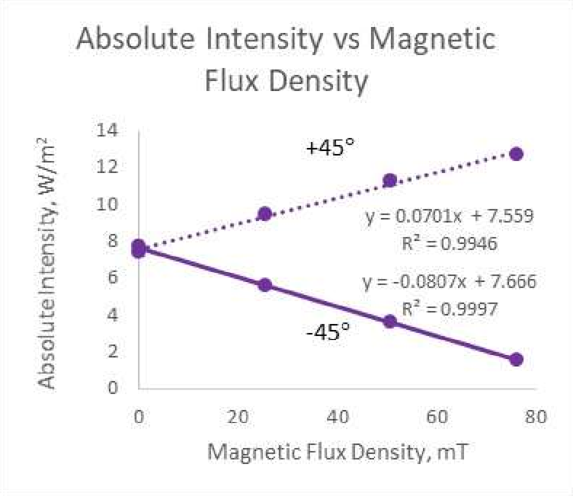


Fig. 3: The relationship between the absolute intensity of 405 nm light and the magnetic flux density produced by the solenoid determined at two different analyzer angles.

As the magnetic flux density increases, the analyzer must be rotated more and more from the crossed position in order to extinguish the light. The magnitude of the rotation needed to extinguish the light is proportional to the magnetic flux density (Fig. 4).

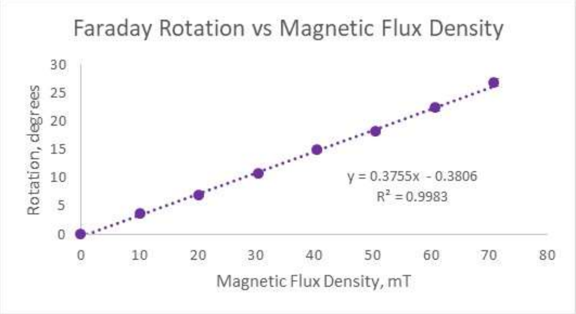


Fig. 4: The relationship between the Faraday rotation angle of 405 nm light and the magnetic flux density produced by the solenoid.

The Verdet constant $V(\lambda)$ for the dielectric (SF-57) at 405 nm light is $3755\,\frac{\text{degree}}{\text{T m}} = 65.50\,\frac{\text{rad}}{\text{T m}}$ as given by the following formula:

$$V(\lambda) = \frac{\theta(\lambda)}{B\ell} \qquad (1)$$

where $\theta(\lambda)$ is the observed rotation at a given wavelength, B is the magnetic flux density, and ℓ is the length of the dielectric (0.1 m). This datum (●) both extends, and is consistent with, the Verdet constants measured in SF-57 for other wavelengths (Fig. 5 includes data from Weber [23] (●) and Phelps et al. [24](o)).

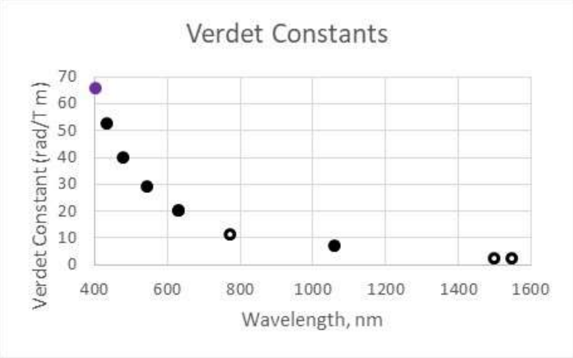


Fig. 5: The Verdet constant of SF-57 as a function of wavelength.

Since the Verdet constant is greater for 405 nm than it is for 632 nm or 650 nm light, a violet laser is superior to a red laser in undergraduate laboratories performing the Faraday rotation experiment [25-27].

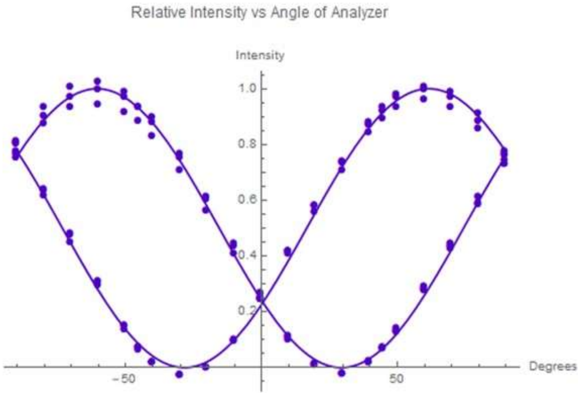


Fig. 6: The effect of the azimuth of the analyzer on the relative intensity of 405 nm light for +7.5 A or -7.5 A of current flowing through the solenoid. When the current is positive, the magnetic flux density is oriented such that the observer is at the South pole and the North pole is at the source end of the electromagnet. When the current is negative, the magnetic flux density is oriented such that the observer is at the North pole and the South pole is at the source end of the electromagnet. The minimum of the curve for +7.5 A is -29.4° ± 0.2°, and the minimum for the curve for -7.5 A is at 28.4° ± 0.2°.

In order to determine the effect of wavelength on the rotation of linearly polarized light, we tried all wavelengths that were available in inexpensive (< $20) and readily available laser pointers. For all wavelengths, the relationship between the relative intensity of the light and the angle of the analyzer is described by a sin^2 function (Fig. 7).

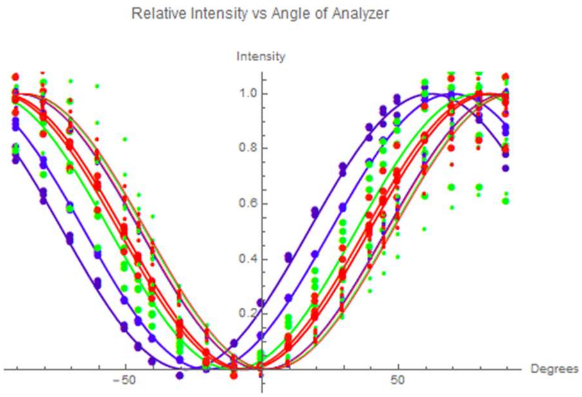


Fig. 7: The effect of the azimuth of the analyzer on the relative intensity of 405 nm (violet), 445 nm (blue), 636 nm (orange),and 650 nm (red) light. Magnetic flux density is either 75.9 mT (thick lines) or 0 mT (thin lines with minima at 0°).

Note that the offset of the minimum, which is equal to the negative of the rotation of the azimuth of polarized light, is proportional to the total energy of the photons (Fig. 8), indicating that the shorter the wavelength ($E = \frac{hc}{\lambda}$), or equivalently, the higher the frequency ($E = h\nu$) of the laser light propagating through the magnetic field, the more the light is rotated. The relationship between the offset and the energy of the photon can also be interpreted in terms of the linear photon density [28].

To understand the optical activity of substances, Fresnel [29,30] considered linearly polarized (LP) light to be composed of a superposition of right- and left-handed circularly polarized (CP) light. An optically active substance has two indices of refraction—one for right circularly polarized light and one for left circularly polarized light. The azimuth (θ) of linearly polarized light propagating through an optically active substance is rotated proportionally to the difference between the refractive index (n_r) of the substance for right-handed circularly polarized light and the refractive index (n_l) for left-handed circularly polarized light according to the following equation:

$$\theta = -\pi \frac{L}{\lambda_o} [n_r - n_l] \tag{2}$$

where L is the physical length of the substance along the direction of light propagation and λ_o is the wavelength of the incident light.

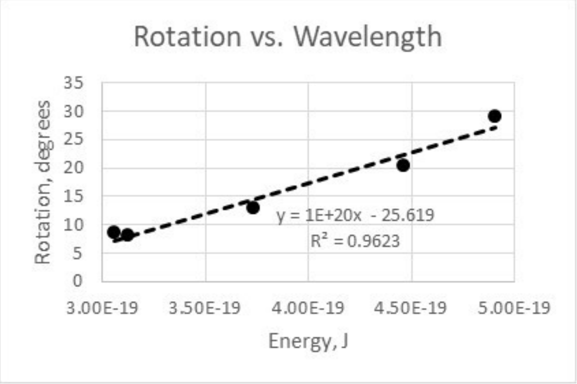


Fig. 8: The relationship between the energy of a photon and the magnitude of the offset of the minima observed in the curves shown in Fig. 7.

Faraday, whose goal was to uncover the unity between light and magnetism, showed that an applied magnetic field can induce optical activity in isotropic "heavy glass" that has a single index of refraction. That is, the application of a magnetic field resulted in the rotation of the azimuth of polarization. While the rotation of the azimuth of polarized light is usually interpreted in terms of the direct effect of the magnetic field on the electrons in the glass and a consequent effect of the electrons on the light propagating through the glass, Faraday rotation can also be interpreted as a direct effect of a magnetic field on "*that which is truly magnetic in the force of light*." Does the magnetic flux density affect the rotation of light by acting directly on the glass, on the light, or on both? And, if the magnetic flux density directly affects light itself, can the Faraday effect be used to elucidate the structure and constitution of light?

Linearly polarized light, which has not been rotated, is equivalent to the superposition of right- and left-handed circularly polarized light of equal amplitude that are in phase [29]. Looking into the source, the right-handed circularly polarized (RCP) light rotates anticlockwise and the left-handed circularly polarized (LCP) light rotates clockwise as they propagate towards the observer. When current flowing with a clockwise sense when looking towards the light source, powers the electromagnet, the light propagating through the SF-57 glass is extinguished when the analyzer is rotated clockwise when looking towards the light source, which means that the light is rotated anticlockwise. This could be explained if the magnetic field caused the refractive index for RCP light to become less than, and the refractive index for LCP light to become greater than, the refractive index of the glass in the absence of a magnetic field. According to Lorentz, the magnetic field influences the refractive index through its effect on the orbiting electrons [12].

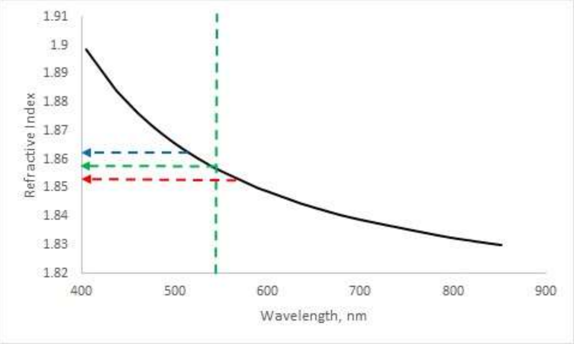


Fig. 9: The relationship between wavelength and the refractive index (n_λ) of SF-57 glass. If the wavelength of half the binary photons that make up the linearly polarized light were blue shifted and the wavelength of the other half of the binary photons that make up the linearly polarized light were red shifted, the azimuth of the linearly polarized light would be rotated

The rotation of the azimuth of polarization of light could also be explained if the wavelength of the light was directly affected by the magnetic field. If the magnetic field caused the RCP light to increase its wavelength and the LCP light to decrease its wavelength, the same result would be obtained because in high dispersion glass with low Abbe numbers, as is required to observe the Faraday effect with a realistic geometrical length of material, the refractive index is lesser for long wavelength light and greater for short wavelength light. Consequently, the long wavelength RCP light would propagate faster through the high dispersion glass than the short wavelength LCP and the azimuth of polarization would rotate anticlockwise. A phase difference between the long and short wavelength binary photons would be introduced that would cause a rotation of the azimuth of the resultant linearly–polarized light. The interpretation that the magnetic flux density directly affects the components of the linearly-polarized light is supported by the fact that the refractive index (n_λ) of SF-57 glass varies inversely with wavelength from 1.945- 1.8 throughout the visible range (Fig. 9). The chromatic dispersion ($\frac{dn}{d\lambda}$) at 405 nm is -739080 m^{-1}: http://refractiveindex.info/?shelf=glass&book=SCHOTT-SF&page=N-SF1

Gedankenexperiment is a term first coined by Hans Christian Oersted in 1811 [31] to describe a method to connect the analysis of *concepts* that describe objects to *real* experiments. A *gedankenexperiment* is a way to form a mental picture of the physical effect of forces on objects. It is possible to create a mental picture of the physical processes that lead to the magnetic flux density-induced rotation of polarized light. Since the Faraday effect is demonstrated by magnets, we will make the connection between the Lorentz force and the orbiting, electrically charged semiphotons that compose the binary photon. We propose that the Lorentz force is a real force that acts on half of the incident binary photons to increase the circumference of the orbits of their semiphotons, and acts on the other half of the incident binary photons to decrease the circumference of the orbits of their semiphotons. The change in orbit circumference is equivalent to a change in wavelength [14].

In the absence of a magnetic field, the circumference of the path of a semiphoton (black circles in Fig. 10) is determined solely by the mass ($\frac{\aleph \mathrm{h}}{2c\lambda}$) and angular momentum ($\pm\frac{\aleph h}{4\pi}$) of a semiphoton where $\aleph$ is +1 for positive mass and -1 for negative mass [32-34]. The circumference of the paths of the semiphotons projected on the plane perpendicular to the axis of propagation is equal to the wavelength (λ) of the binary photon [14,15,19]. The parity (P) of the semiphotons along the path is equal to ± 1, where $P = +1$ for anticlockwise rotation and -1 for clockwise rotation when looking at the source of the light. When the four classes of binary photon are not exposed to a magnetic field, they all have the same projected semiphoton path circumference and wavelength (black circles in Fig. 10).

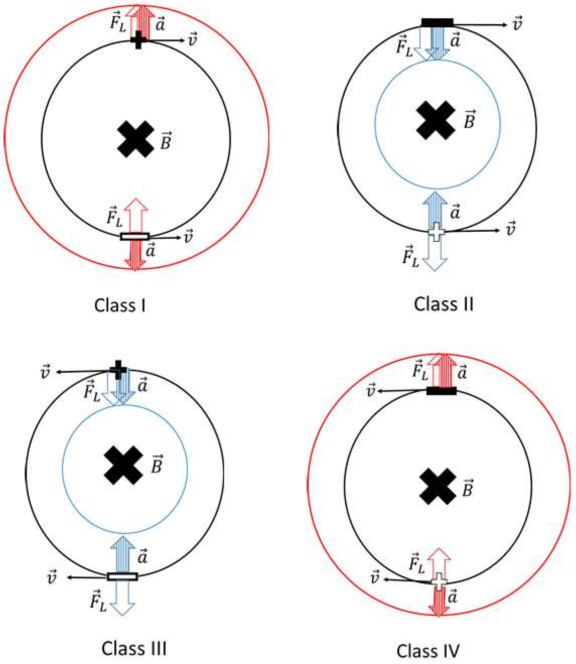
In the presence of a magnetic flux density ($\vec{B}$), a Lorentz force ($\vec{F}_L$) is exerted on the leading semiphoton. The Lorentz force on the leading semiphoton is given by the product of the mass coefficient ($\aleph = +1$) and the charge (q) of the semiphoton ($\aleph q$) multiplied by the cross product of the velocity ($\dot{\vec{r}}$) of the leading semiphoton and the magnetic flux density [32-34]. When the magnetic flux density is antiparallel to the direction of light propagation, the Lorentz force on the leading semiphoton is outwardly directed in Class I and Class IV binary photons and inwardly directed in Class II and Class III binary photons. The Lorentz force on the following semiphoton which has a negative mass ($\aleph = -1$) is inwardly directed in Class I and Class IV binary photons and outwardly directed in Class II and Class III binary photons. The Lorentz force shown in Fig. 10 on each semiphoton in each of the four classes of binary photon can be checked by applying the right-hand rule using Eqn. (3).

The inertial force ($m\ddot{\vec{r}}$) exerted on the positive or negative mass semiphotons is related to the Lorentz force by the following equation:

$$\vec{F}_L = \aleph q\dot{\vec{r}} \times \vec{B} = m\ddot{\vec{r}} \qquad (3)$$[1]

where m is the positive or negative mass of the semiphoton and $\ddot{\vec{r}}$ is its radial acceleration. Consequently, as the binary photon propagates through the magnetic field, a Lorentz force results in a radial acceleration of the semiphotons. The radial acceleration of the positive mass leading semiphoton is parallel to the Lorentz force and the radial acceleration of the negative mass following semiphoton is antiparallel to the Lorentz force. Consequently, both semiphotons in a given binary photon accelerate either centrifugally or centripetally. Centrifugal acceleration results in an increase in the circumference and wavelength of the binary photon and centripetal acceleration results in a decrease in the circumference and wavelength of the binary photon. Fig. 10 shows how a magnetic field running antiparallel to the direction of light propagation accelerates the semiphotons in class I and class II binary photons to increase the circumference and accelerates the semiphotons in class II and class III binary photons to decrease the circumference and wavelength of the binary photon.

In any given binary photon, the two semiphotons accelerate in the same direction so that the Lorentz force results in an increase or decrease in the wavelength of the binary photon. As a consequence of the high dispersion of "heavy glass," the long wavelength class I and class IV binary photons experience a lower refractive index propagating through the "heavy glass" than the short wavelength class II and class III binary photons when the magnetic field is antiparallel to the direction of light propagation. Since the azimuth of polarization is rotated anticlockwise in response to a magnetic field in the experiments described, we can infer that the class I and class IV binary photons make up the right-handed circularly polarized (RCP) light and the class II and class III binary photons make up the left-handed circularly polarized (LCP) light.



Class I

Class II

Class III

Class IV

Fig. 10: Schematic of the effect of a magnetic flux density ($\vec{B}$) directed into the paper (×) on the circumference of four classes of binary photons propagating towards the reader. A clockwise current flowing through the solenoid produces a magnetic flux density that runs S → N antiparallel to the direction of propagation. The leading semiphoton, which always has a positive mass (M), is shown on the top of the projection of its path (black circle) on the transverse plane and the following semiphoton, which always has a negative mass, is shown on the bottom of the projection of its path (black circle) on the transverse plane for each class of binary photon. The electric charge (C) on the positive mass semiphoton is shown as a black + or − and as a white + or − on the negative mass semiphoton. The direction of the velocity vector ($\vec{v}$) of the semiphotons is determined by the sign of the parity (P), which is +1 for anticlockwise motion and -1 for clockwise motion. The Lorentz force ($\vec{F}_L = \aleph q\dot{\vec{r}} \times \vec{B}$) exerted on the leading and following semiphotons in each class of binary photon is shown by empty red or blue arrows. The radial acceleration ($\vec{a} = \vec{F}_L/m$) on the leading and following semiphotons

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[1] Eqn. (3) ($\vec{F}_L = \aleph q\dot{\vec{r}} \times \vec{B} = m\ddot{\vec{r}}$) can be written for positive and negative mass without using the unfamiliar ℵ but the signed mass must be replaced with the modulus of the mass ($\vec{F}_L = q\dot{\vec{r}} \times \vec{B} = |m|\ddot{\vec{r}}$). The latter form of the equation, which does not take into consideration the sign of the mass, can also be written in a way that is consistent with CPT symmetry. This is done by reversing the velocity of the following semiphoton so that it moves backwards in time. It is also possible to emphasize the noncommutative nature of the Lorentz force on positive and negative mass by using $\vec{F}_L = q\dot{\vec{r}} \times \vec{B} = |m|\ddot{\vec{r}}$ for positive mass and $\vec{F}_L = q\vec{B} \times \dot{\vec{r}} = |m|\ddot{\vec{r}}$ for negative mass.

is shown by stripped red or blue arrows. For the leading semiphotons, the acceleration is always parallel to $\vec{F}_L$ and for the following semiphotons, the acceleration is always antiparallel to $\vec{F}_L$. In class I and class IV binary photons, the Lorentz force on the positive mass leading semiphoton is centrifugal, which results in a centrifugal acceleration, and the Lorentz force on the negative mass following semiphoton is centripetal, which also results in a centrifugal acceleration. The two centrifugal accelerations result in an increase in the circumference (red circle) of the binary photon, which is equivalent to an increase in wavelength. In class II and class III binary photons, $\vec{F}_L$ on the leading semiphoton is centripetal, which results in a centripetal acceleration, and $\vec{F}_L$ on the following semiphoton is centrifugal, which also results in a centripetal acceleration. The two centripetal accelerations result in a decrease in the circumference (blue circle) of the binary photon, which is equivalent to a decrease in wavelength.

If the current (i) in the electromagnet were reversed so that it flowed anticlockwise and the magnetic field lines were parallel to the direction of propagation, the Lorentz force would cause an increase in the wavelength of the class II and class III binary photons, and a decrease in the wavelength of the class I and class IV binary photons (Appendix). Consequently, the class I and class IV binary photons would experience a higher refractive index propagating through the glass than the class II and class III binary photons, and the azimuth of polarization would be rotated clockwise. Thus, we can still infer that, in a magnetic field that runs parallel to the direction of light propagation, the class I and class IV binary photons make up the RCP light and the class II and class III binary photons make up the LCP light.

The magnetic flux density though the "heavy glass" results in a transformation of the intrinsic wavelength of the binary photons. This is equivalent to a change in the intrinsic frequency, the intrinsic energy, and the intrinsic linear momentum of the binary photon [28]. While the magnetic flux density can be considered as an agent that transforms the incident binary photons to complementary binary photons with longer and shorter wavelengths, it can also be considered as a magnetic prism that resolves the binary photons into two complementary components that differ in their magnetic properties. One component of natural light consists of the class I and class IV binary photons and the other component consists of the class II and class III binary photons. The first resolved component, which includes class I and class IV binary photons, has a magnetic moment that is antiparallel to the direction of propagation and the second resolved component, which includes class II and class III binary photons, has a magnetic moment that is parallel to the direction of propagation [14,15]. When the magnetic flux density is antiparallel to the direction of light propagation, the magnetic momenta of the red-shifted class I and class IV binary photons are parallel to the magnetic flux density and the magnetic momenta of the blue-shifted class II and class III binary photons are antiparallel to the magnetic flux density. That is, the binary photons whose magnetic momenta are parallel to the magnetic flux density have a lower energy and the binary photons whose magnetic momenta are antiparallel to the magnetic flux density have a higher energy.

In order to analyze the magnetic flux density-induced change in wavelength using electrodynamic principles, we give the radial acceleration in Eqn. (3) in terms of its components:

$$\ddot{\vec{r}} = \ddot{x}\hat{x} + \ddot{y}\hat{y} \tag{4}$$

This analysis, which characterizes the forces on the semiphotons that rotate along orbits that are projected on the plane ($\hat{x}\hat{y}$) orthogonal to the axis of propagation ($\hat{z}$), are based on Hooke's law, Newton's second law, and the Lorentz force law.

Assume that that $\vec{F}$ is a central force dependent on the conservation of angular momentum [17] that holds the semiphotons in an orbit with radius r when projected on the transverse plane ($\hat{x}\hat{y}$), where r is related to the wavelength, frequency, and angular frequency of the semiphoton such that $r = \frac{\lambda}{2\pi} = \frac{c}{2\pi\nu} = \frac{c}{\omega} = \frac{1}{k}$. Since the radius of the orbit is inversely proportional to the angular frequency of the semiphoton, then

$$\vec{F} = -m\omega_o^2\vec{r} \tag{5}$$

where $m = \frac{\aleph\hbar\omega}{2c^2} = \frac{\aleph h}{2c\lambda}$ is the mass of the semiphoton and ω_o is the natural angular frequency of rotation of the semiphoton and is equal to the ratio of the energy of the semihoton to $\frac{\hbar}{2}$. Eqn. (5) can be put in the form of Hooke's law:

$$\vec{F} = -K\vec{r} \tag{6}$$

where K is the spring constant equal to $m\omega_o^2$.

At equilibrium, where the orbit maintains a constant radius, $\vec{F} = m\ddot{\vec{r}}$. According to Newton's second law,

$$m\omega_o^2\vec{r} = m\ddot{\vec{r}} \tag{7}$$

Thus

$$m\omega_o^2(x\hat{x} + y\hat{y}) = m(\ddot{x}\hat{x} + \ddot{y}\hat{y}) \tag{8}$$

And after cancelling like terms, and resolving the components, we get:

$$\omega_o^2 x = \ddot{x} \tag{9a}$$

$$\omega_o^2 y = \ddot{y} \tag{9b}$$

After combining Eqns. (9a) and (9b), we get:

$$\omega_o^2 = \frac{\ddot{x}}{x} = \frac{\ddot{y}}{y} \tag{10}$$

In the presence of a magnetic flux density, the semiphotons experience the magnetic component of the Lorentz force. After combining Eqns. (3) and (4) and letting $\vec{B} = B\hat{z}$, we get:

$$\vec{F}_L = \aleph q B(\dot{x}\hat{y} + \dot{y}\hat{x} + \dot{z}\hat{z}) \times \hat{z} \tag{11}$$

Since $\hat{z} \times \hat{z} = 0$, we get:

$$\vec{F}_L = \aleph q B(\dot{x}\hat{y} + \dot{y}\hat{x}) \tag{12}$$

Using $\ddot{\vec{r}} = \ddot{x}\hat{x} + \ddot{y}\hat{y}$, in the presence of the Lorentz force, Newton's second law becomes:

$$\aleph q B(\dot{x}\hat{y} + \dot{y}\hat{x}) = m(\ddot{x}\hat{x} + \ddot{y}\hat{y}) \tag{13}$$

The components of which are:

$$\frac{\aleph q}{m}B(\dot{x}_b) = \ddot{y} \tag{14a}$$

$$\frac{\aleph q}{m}B(\dot{y}_b) = \ddot{x} \tag{14b}$$

Since $\dot{x} = \omega_b x$ and $\dot{y} = \omega_b y$, the above equations become:

$$\frac{\aleph q}{m}B(\omega_b x) = \ddot{y} \tag{15a}$$

$$\frac{\aleph q}{m}B(\omega_b y) = \ddot{x} \tag{15b}$$

The effect of the magnetic flux density on the acceleration of a semiphoton in the projection on the transverse plane ($\hat{x}\hat{y}$) is:

$$\ddot{x}_b = \omega_o^2 x \pm \frac{\aleph q}{m}B(\omega_b y) \tag{16a}$$

$$\ddot{y}_b = \omega_o^2 y \pm \frac{\aleph q}{m}B(\omega_b x) \tag{16b}$$

Substituting ω_b^2 for ω_o^2 and $(\ddot{x}_b\hat{x} + \ddot{y}_b\hat{y})$ for $(\ddot{x}\hat{x} + \ddot{y}\hat{y})$ in Eqn. (8), and resolving the components, we get:

$$\omega_b^2 x = \omega_o^2 x \pm \frac{\aleph q}{m}B(\omega_b y) \tag{17a}$$

$$\omega_b^2 y = \omega_o^2 y \pm \frac{\aleph q}{m}B(\omega_b x) \tag{17b}$$

And for circular motion, $x = y$, thus Eqns. (17a) and (17b) become:

$$\omega_o^2 - \omega_b^2 = \mp \frac{\aleph q}{m}B(\omega_b) \tag{18}$$

We can solve for ω_b:

$$\omega_o^2 - \omega_b^2 = (\omega_o + \omega_b)(\omega_o - \omega_b) \tag{19}$$

As long as $\omega_o \gg \left|\frac{\aleph q}{2m}\right| B$ and $\omega_o \cong \omega_b$ then $\omega_o + \omega_b \cong 2\omega_b$, and

$$(\omega_o + \omega_b)(\omega_o - \omega_b) \cong 2\omega_b(\omega_o - \omega_b) \tag{20}$$

From Eqn. (18) we see that:

$$(\omega_o + \omega_b)(\omega_o - \omega_b) = \mp \frac{\aleph q}{m}B(\omega_b) \tag{21}$$

After substituting Eqn. (20) into Eqn. (21), we get:

$$2\omega_b(\omega_o - \omega_b) \cong \mp \frac{\aleph q}{m}B(\omega_b) \tag{22}$$

After cancelling like terms, we get:

$$\omega_o - \omega_b \cong \mp \frac{\aleph q}{2m}B \tag{23}$$

Thus

$$\omega_{b+} \cong \omega_o + \frac{\aleph q}{2m}B \tag{24a}$$

$$\omega_{b-} \cong \omega_o - \frac{\aleph q}{2m}B \tag{24b}$$

Let $\partial\omega = \omega_{b+} - \omega_{b-}$, then

$$\partial\omega = \frac{\aleph q}{m}B \tag{25}$$

Since $\omega = 2\pi\nu$, then

$$\partial\nu = \frac{\aleph q}{2\pi m}B \tag{26}$$

Since $\nu\lambda = c$ and $\partial\nu = -\frac{c}{\lambda_o^2}\partial\lambda$, we get:

$$\partial\lambda = -\lambda_o^2 \frac{\aleph q}{2\pi m c}B \tag{27}$$

Eqn. (27) shows the effect of magnetic flux density on changing the wavelength and the circumference of the binary photons. Since for a semiphoton, $m = \frac{\aleph h}{2c\lambda_o}$, we get:

$$\partial\lambda = -\lambda_o^3 \frac{q}{\pi h} B \tag{28}$$

where for 405 nm light, if $q = 1.60 \times 10^{-1}$ C, $\partial\lambda = 5106$ nm/T or 5.106 nm per milliTesla if the magnetic flux density only affected the semiphotons.

However, the magnetic energy added to the system composed of "heavy glass" and light will be partitioned between the electrons in the "heavy glass" and the semiphotons in the binary photons propagating through the "heavy glass." Since the electron mass is approximately 400,000 times greater than the modulus of the mass of the semiphotons, the wavelength differential, which would indicate a direct effect of the magnetic flux density on the magnetic properties of light, would be modest compared to the refractive index differential. The ratio of the differential in refractive index (∂n) to the differential in wavelength ($\partial\lambda$) can be estimated from the Verdet constant using the Becquerel formula [35] as modified by Darwin and Watson [36], Serber [37], and Ramaseshan [38]:

$$V(\lambda) = -\gamma \frac{e}{2mc} \lambda_o \frac{\partial n}{\partial \lambda} \tag{29}$$

where $e = 1.60 \times 10^{-19}$ C, $m = 9.11 \times 10^{-31}$ kg, $\lambda_o = 405 \times 10^{-9}$ m, and c = 3 × 10^8 m/s We calculated the value of the magneto-optic anomaly of the "heavy glass" from our measurement of the Verdet constant at 405 nm ($65.50 \frac{\text{rad}}{\text{T m}}$). Using $\frac{dn}{d\lambda}(405 \text{ nm}) = -739080$ m^{-1}, the magnetic anomaly (γ) is 0.748, which is a reasonable value [36-38]. Consequently, if $\frac{dn}{d\lambda} = -739080$ m^{-1}, $\partial\lambda = -\partial n/739080$. If we estimate ∂n to be approximately 0.01, which is a reasonable value for optically active materials, then $\partial\lambda$ would be about 13 nm per Tesla or 0.013 nm per milliTesla, which could be measured with a spectrometer and would indicate the direct effect of the magnetic flux density on binary photons.

Since the refractive index of the high dispersion "heavy glass" is wavelength dependent, the "heavy glass" has one effective refractive index for the nominal wavelength of the laser in the absence of a magnetic flux density and two effective refractive indices in the presence of a magnetic flux density. This results in the rotation of the azimuth of polarization as first observed by Faraday.

Faraday was not able to resolve a magnetic flux density-induced differentiation of the wavelength of light with the equipment he had, but Pieter Zeeman was. Zeeman [8] discovered that when he placed a sodium flame between two poles of an electromagnet, the two D lines were broadened. Hendrik Lorentz [12] realized that this was consistent with his electron theory of matter and predicted that the light viewed parallel to the magnetic flux density lines should be circularly polarized with opposite senses, and that light viewed perpendicular to the magnetic flux density lines should be linearly polarized, where the azimuth of polarization of the center of the line is parallel to the magnetic flux density lines and the azimuth of polarization of the sides of the line is perpendicular (*senkrecht*) to the magnetic flux density lines. Lorentz's predictions were verified by Zeeman. Later is was discovered that the number of line splittings observed was even greater than Lorentz predicted, and while this is known as the anomalous Zeeman effect, it is the typical case. The additional splittings are usually accounted for by taking into consideration the magnetic moment ($\pm\mu$) that results from the intrinsic spin of the electron. The model of the binary photon can also account for the additional splittings by taking into consideration the two possible orientations of the magnetic moment ($\pm\mu$) of the binary photons [14,39,40]. In a cloud of incandescent atoms used to demonstrate the Zeeman effect, binary photons with magnetic moments parallel and antiparallel to the direction of propagation would cross the magnetic flux density lines at an angle θ and thus experience a torque that would increase or decrease the energy of the binary photon by ΔE as the propagation path is bent along the magnetic flux density lines according to the following equation (Fig. 11):

$$\Delta E = \mu B \sin\theta \tag{30}$$

Thus, while the magnetic moment of the binary photon has no effect in terms of the Faraday effect since the light propagates parallel or antiparallel to the magnetic flux density lines, the two orientations of the magnetic moment provides the mechanism needed to explain the splitting observed in the anomalous Zeeman effect.

Just as the Faraday effect can be used to interrogate the nature of light in that it demands that photons have the attribute of "*that which is truly magnetic in the force of light*." The wavelength splittings observed in the longitudinal or transverse Zeeman effect can also be used to probe the binary photon further in that Eqn. (28) can be used to determine the absolute magnitude of the charge of each semiphoton in a binary photon.

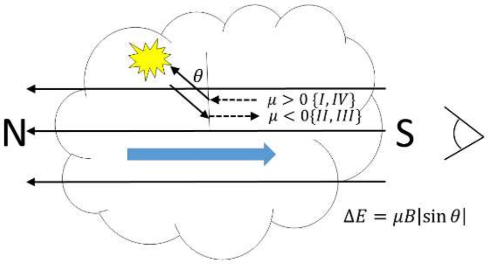

Fig. 11. An incandescent atom emits binary photons with each with a magnetic moment parallel or antiparallel to the direction of propagation. When these binary photons cross the magnetic flux density lines, they experience a torque that bends them so that their magnetic moments are either parallel to antiparallel to the magnetic flux density lines and this torque increases or decreases their total energy. Blue arrow indicates a direction of propagation antiparallel to the magnetic flux density lines.

Rereading Faraday after finishing the experiments presented here, we wanted to experience his exciting observation with a candle flame instead of a laser. Faraday [4] wrote, "*the force of the electro-magnet was developed, by sending an electric current through its coils, and immediately the image of the lamp flame became visible, and continued so as long as the arrangement continued magnetic. On stopping the electric current, and so causing the magnetic force to cease, the light instantly disappeared; these phenomena could be renewed at pleasure, at any instant of time, and upon any occasion, showing a perfect dependence of cause and effect*." We happily found that the flame from a bayberry candle purcased from Thomas Jefferson's (1743-1826) Monticello appeared bright through crossed polars when we turned on the magnetic flux density and dimmed to near invisibility when we shut off the magnetic flux density—confirming Faraday's (1791-1867) original observation (Fig. 12).

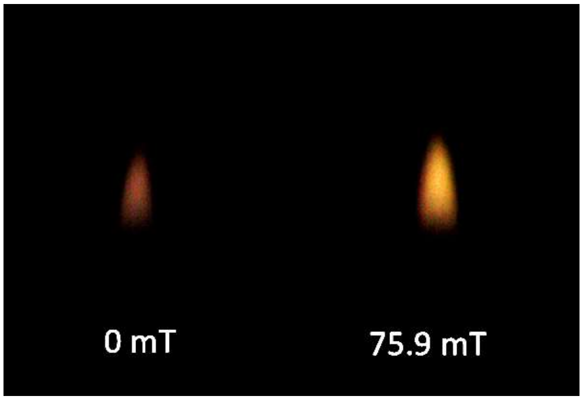

Fig. 12: The image of the flame from a bayberry candle viewed through crossed polars when the magnetic flux density was off (0 mT) or on (75.9 mT). The dim image seen at 0 mT is due to strain birefringence of the "heavy glass." The image was taken through a TV Zoom 12.5-75 mm f/11.8 lens with an Amscope MU 300 camera using ToupView image capturing software and the brightness and contrast were adjusted with ImageJ.

4. Conclusion

Michael Faraday was one of the world's greatest scientists [41-54]. Einstein kept a picture of Faraday on his study wall [55]. Aldous Huxley [56], the literary giant who was also the grandson of T. H. Huxley, the grandnephew of Matthew Arnold, the brother of Julian Huxley, and the half-brother of Andrew Fielding Huxley, wrote about Faraday: "*He is always the natural philosopher. To discover truth is his sole aim and interest…even if I could be Shakespeare, I think I should still choose to be Faraday*."

Many may be surprised to learn that Faraday had little formal education before he became an apprentice at age 13 to George Riebau, the bookseller. Faraday [44] wrote, "*My education was of the most ordinary description, consisting of little more than the rudiments of reading, writing, and arithmetic at a common day-school*." With little mathematical ability but exceptional experimental technique and physical insight, Faraday created physical pictures of the phenomena he revealed as he performed his experiments. Successors to Faraday, who were better trained in mathematics and positivists in worldview, began to see physical pictures as superfluous at best and more often saw them as misleading. Consequently, mathematical equations replaced the physical pictures Faraday described.

Maxwell [57] impressed on his students the importance of understanding the principles upon which mathematical equations were based. Maxwell wrote, "*In this class, I hope you will learn not merely results, or formulae applicable to cases that may possibly occur in our practice afterwards, but the principles on which those formulae depend, and without which the formulae are mere mental rubbish. I know the tendency of the human mind is to do anything rather than think. But mental labour is not thought, and those who have with labour acquired the habit of application often find it much easier to get up a formula than to master a principle*."

In his sequel to Maxwell's Treatise, J. J. Thomson [58] wrote, "*I have found that students, especially* *those who commence the subject after a long course of mathematical studies, have a great tendency to regard the whole of Maxwell's theory as a matter of the solution of certain differential equations, and to dispense with any attempt to form for themselves a* ***mental picture*** *of the physical processes which accompany the phenomena they are investigating. I think that this state of things is to be regretted, since it retards the progress of the science of Electricity and diminishes the value of the mental training afforded by the study of that science.*

In the first place, though no instrument of research is more powerful than Mathematical Analysis, which indeed is indispensable in many departments of Electricity, yet analysis works to the best advantage when employed in developing the suggestions afforded by other and more physical methods. One example of such a method, and one which is very closely connected with the initiation and development of Maxwell's Theory, is that of the 'tubes of force' used by Faraday. Faraday interpreted the laws of Electrostatics in terms of his tubes, which served him in the laws according to which these tubes acted on each other served instead of the differential equations satisfied by such symbols. The method of the tubes is distinctly physical, that of the symbols and differential equations is analytical. The physical method has all the advantages in vividness which arise from the use of concrete quantities instead of abstract symbols used to represent the state of the electric field; it is more easily wielded, and is thus more suitable for obtaining rapidly the main features of any problem; when, however, the problem has to be worked out in all its details, the analytical method is necessary.

In a research in any of the various fields of electricity we shall be acting in accordance with Bacon's dictum that the best results are obtained when a research begins with Physics and ends with Mathematics, if we use the physical theory to, so to speak, make a general survey of the country, and when this has been done use the analytical method to lay down firm roads along the line indicated by the survey.

The use of a physical theory will help to correct the tendency—which I think all who have had occasion to examine in Mathematical Physics will admit is by no means uncommon—to look on analytical processes as the modern equivalents of the Philosopher's Machine in the Grand Academy of Lagado[2]*, and to regard as the normal process of investigation in this subject the manipulation of a large number of symbols in the hope that every now and then then some valuable result may happen to drop out.*

Then, again, I think that supplementing the mathematical theory by one of a more physical character makes the study of electricity more valuable as a mental training for the student. Analysis is undoubtedly the greatest thought-saving machine ever invented, but I confess I do not think it necessary or desirable to use artificial means to prevent students from thinking too much. It frequently happens that more thought is required, and a more vivid idea of the essentials of a problem gained, by a rough solution by a general method, than by a complete solution arrived at by the most recent improvements in the higher analysis.

… the question as to which particular method the student should adopt is however for many purposes of secondary importance, provided that he does adopt one, and acquires the habit of looking at the problems with which he is occupied as much as possible from a physical point of view."

J. J. Thomson [60], incorporated mental pictures into his own model of the photon which considered the photon to be a closed ring composed of an electric tube of force.

Michael Faraday thought of the physical phenomena he discovered and studied in terms of mental pictures. Faraday [2], who is pictured in Fig. 13 holding a piece of "heavy glass," wrote, "*I believe that, in the experiments I describe in the paper, light has been magnetically affected, i. e. that that which is magnetic in the forces of matter have been affected, and in turn has affected that which is truly magnetic in the force of light*." One of us has published animations of the binary photon that show the electric and magnetic lines of force [17]—lines of force that describe and explain "*that which is truly magnetic in the force of light*." Here we have shown that the model of the binary photon can account for magneto-optical phenomena, including the Faraday effect, the Zeeman effect, and the anomalous Zeeman effect [61,62].

The binary photon model proposes that the photon is not an elementary particle but a complex of two particles that are conjugate in terms of mass, electric charge, and sense of rotation, whose movements

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[2] From *Gulliver's Travels* by Jonathan Swift [59].

generate a linearly polarized transverse electric field and a circularly polarized magnetic flux density that is orthogonal to the electric field and a quarter wavelength out-of-phase with it [15]. The binary photon contains an electric dipole and a magnetic moment, which logically seem to be a *sine qua non* for the carrier of the electromagnetic force, and may contribute to the hidden variables that could illuminate the true nature of light. Compared with a mathematical point-like photon or an infinite plane wave, the binary photon encompasses "*that which is truly magnetic in the force of light.*"

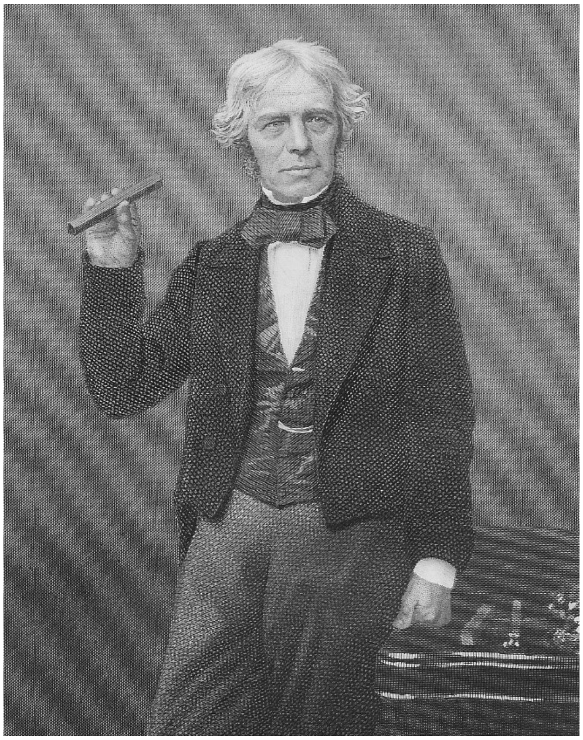

Fig. 13: Michael Faraday holding a piece of "heavy glass." Cropped photograph from Dr. Bence Jones, *The Life and Letters of Faraday*. Volume I. Second edition (Longmans, Green, and Co., London, 1870).

The model of the binary photon is based on the assumptions that negative mass exists, that antimatter is better described by charge-parity-mass (CPM) symmetry than by charge-mass-time symmetry (CPT), and that the vacuum is empty [32,33,63]. The success of the model of the binary photon in describing and explaining the Faraday effect provides further support for the value of CPM symmetry in providing a new way of organizing a large number of isolated facts, in giving new insight into their connections with each other, and in allowing us to predict new facts [16,34,64].

If light, as characterized by binary photons, is magnetic because it is composed of moving charges, it is possible for the magnetic flux density to rotate the azimuth of polarization by acting directly on the binary photons themselves. If light is characterized as being composed of mathematical point-like photons that contain no charge, then the magnetic flux density that causes the rotation of polarized light must act directly on the glass itself, and the mechanism of the action of the glass on light itself remains enigmatic. According to Hans Christian Oersted [65], who was the first person to discover the relationship between electricity and magnetism, "*an hypothesis which is permitted in the system of science ought only to relate to the connection between a cause or a universal law of nature, of whose existence we are certain, and whose action or more limited natural law we would from it explain*." According to Max Jammer [66], "*For unless a formalism is linked with certain data of sensory experience in such a way that both the beginning and the end of a chain of theoretical deductions are anchored in experience, it is not verifiable or falsifiable by experiment or observation and consequently not a physical theory*." Without such a physical theory, a formalism is only an *ignotum per ignotius*—an explanation of an unknown in terms of something that is more unknown.

Here we have used the universally-accepted laws of nature proffered by Newton, Hooke, and Lorentz to explain the dynamic effects of an electromagnet on the rotation of the linearly-polarized electric field of light propagating through high dispersion glass. We have done this by replacing the accepted ideas of negative time and reversibility that go with the mathematical point-like photon with the concepts of negative mass and irreversibility that go with the binary photon [67]. The correct explanation of the Faraday effect depends upon the true nature of time and the true nature of the photon—the boson that is the carrier of the electromagnetic force. Is light composed of mathematical point-like photons whose unpicturable characteristics can only be described by numbers, or is light composed of binary photons composed of two rotating and oscillating semiphotons that are conjugate in terms of mass, electric charge, and parity and whose dynamics can be causally-influenced in known ways by the electromagnet?

Hendrik Lorentz [68] thought about the size of a photon, and wrote on May 6, 1909 to Einstein, who originated the idea of the photon as a mathematical point, "*I find it hard to subscribe to the view that the light quanta retain a certain individuality even during their propagation, as if one were dealing with "punctiform" energy quantities or at least energy* *quantities concentrated in very small volumes. It seems to me that it can easily be shown that a light quantum can have a considerable extension in the direction of propagation as well as perpendicularly to it, and that under certain circumstances only a part of a light quantum reaches the retina and brings about the perception of light…. I would very much like to hear your opinion about the views I have expounded. In conclusion, permit me to say how glad I am that these problems of radiation theory have given me a chance to enter into a personal relationship with you, after having admired your papers for such a long time*."

Einstein [69], who found Lorentz to be an "*amazingly profound and at the same time lovable man* [70]" answered Lorentz on May 23, 1909 "*As far as the light quanta are concerned, it seems that I did not express myself clearly. For I am not at all of the opinion that light has to be thought of as being composed of mutually independent quanta localized in relatively small spaces. To be sure, this would be the most convenient way to explain the Wien end of the radiation formula. But the splitting of light rays on the surfaces of refracting media already makes this approach absolutely inadmissible. A light ray splits, but a light quantum cannot split without a change in frequency….*

I believe that the light groups around singular points in a way similar to what we are accustomed to assume for the electrostatic field. Thus, I think of a single light quantum as a point surrounded by a greatly extended vector field that somehow decreases with distance. The point is a singularity without which the vector field cannot exist. I wouldn't know to say whether one has to envision a simple superposition of the vector fields when many light quanta with mutually overlapping fields are present. In any case, in order to determine the processes one would also have to have equations of motion for the singular points in addition to the differential equations for the vector field, if mathematical singularities are introduced."

Lorentz continued to ponder the size of the photon. He wrote [71], "*the discrepancy between these estimates of the size of a quantum, according to which it would be too big to enter our eye, and, on the other hand, the notion that it is small enough to be captured by a single electron, is certainly very wide. Yet the laws of the two classes of phenomena about which we have reasoned, the phenomena of interference and those of photo-electricity, are so well established that there can be no real contradiction between what we deduce from one class and from the other; it must after all be possible to reconcile the different ideas. Here is an important problem for the physics of the immediate future. We cannot help thinking that the solution will be found in some happy combination of extended waves and concentrated quanta, the waves being made responsible for interference and the quanta for photo-electricity*." The binary photon [15-19,72] is a "*happy combination of extended waves and concentrated quanta*."

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Appendix

Table: Shifts in the wavelength that result for each of the four classes of binary photon when the magnetic field lines are antiparallel or parallel to the direction of light propagation. The semiphotons are defined by their charge (C), parity (P), and mass (M). An uppercase letter signifies a positive value; a minus sign signifies a negative value in the corresponding position. The CPM traits of the two semiphotons always complement one another.

Class	Leading Semiphoton	Following Semiphoton	Magnetic Field	Lorentz Force on Leading Semiphoton	Lorentz Force on Following Semiphoton	Acceleration of Leading Semiphoton	Acceleration of Following Semiphoton	Shift	Circular Polarization[a] in a Magnetic Field
I	C − M	− P −	Antiparallel	outward	inward	outward	outward	Red	right
II	− − M	C P −	Antiparallel	inward	outward	inward	inward	Blue	left
III	C P M	− − −	Antiparallel	inward	outward	inward	outward	Blue	left
IV	− P M	C − −	Antiparallel	outward	inward	outward	inward	Red	right
I	C − M	− P −	Parallel	inward	outward	inward	inward	Blue	right
II	− − M	C P −	Parallel	outward	inward	outward	outward	Red	left
III	C P M	− − −	Parallel	outward	inward	outward	outward	Red	left
IV	− P M	C − −	Parallel	inward	outward	inward	inward	Blue	right

[a] The rotation of the azimuth of polarized light is anticlockwise when the magnetic field lines are antiparallel to the direction of light propagation and clockwise when the magnetic field lines are parallel to the direction of light propagation. Consequently, class I and class IV binary photons make up the right-handed circularly polarized light and the class II and class III binary photons make up the left-handed circularly polarized light. The right- and left-handed circularly polarized light observed in a magnetic field do not represent the electric field of the binary photon, which is linearly polarized but have to do with the magnetic moments of the binary photon which are antiparallel to the direction of propagation in class I and class IV binary photons and parallel to the direction of propagation in class II and class III binary photons [15].