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Arago, Biot, and Fresnel Elucidate Circular Polarization
Frédéric LECLERCQ*

Abstract: François Arago, Jean-Baptiste Biot, and Augustin Fresnel successively studied circular polarization on the basis of previous chromatic polarization research. But it is perhaps circular polarization that best shows the limits of corpuscular theory and the full potential of its wave theory rival. This article examines that debate.

Keywords: François Arago; Jean-Baptiste Biot; Augustin Fresnel; depolarization; rotatory polarization.

The earlier chromatic polarization results form the basis for all later circular polarization research, so we will first clarify the former in order to facilitate the description and explanation of the latter. Towards the end of 1810, François Arago discovered that, when polarized light was shone through birefringent crystals, colors were produced. His observations, made public in 1811, left no doubt about the distinction between chromatic and circular polarization, even though they were described in terms similar to the concepts handed down from Étienne-Louis Malus. In 1811–1812, Jean-Baptiste Biot used a Laplacian physics framework to study the chromatic polarization of light and also investigated circular polarization. While the former was remarkable, and was supported by a bold mechanical model, the success of the latter was...
not as immediately apparent. In a follow-up, only made public in 1818, Biot stated the experimental law of circular polarization. However, he was unable to give a physical interpretation, and this undoubtedly marks the limit of Laplacian physics as it applies to polarization. In parallel, the wave theory of light was making progress—from 1815 onwards, Augustin Fresnel successfully applied the principle of interference to chromatic polarization, basing this on his work with birefringent crystals. As circular polarization does not seem to result from double refraction, but has color patterns displaying some similarities with those of chromatic polarization, Fresnel studied it in relation to the latter. In 1817–1818, he managed to reproduce Biot's experimental results on circular polarization, thereby extending the generality of the interference principle and increasing the plausibility of the wave theory of light. While Fresnel did not mention the transverse wave hypothesis implicit in these polarization studies,¹ it nevertheless became much more likely. Note that all contemporary research on circular polarization was carried out by these three French scientists; their English counterparts published nothing.²

At the beginning of the nineteenth century, Isaac Newton’s work on light carried even more authority than that of Laplacian science,³ and it is in this scientific context that Malus discovered in 1808 a new property acquired by a reflected beam of light, that of polarization.⁴ This phenomenon, consisting of a change in the intensity of a polarized ray of light in directions perpendicular to its

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¹ - Credited by Fresnel to André-Marie Ampère in 1816, it appears in an unpublished handwritten note—Œuvres complètes d’Augustin Fresnel I (Paris: Imprimerie impériale, 1866), 394—with a view to making the wave theory acceptable to the members of the French Institute. Arago, who was always skeptical about a transverse mechanical motion in the ether (ibid, 635) restrained Fresnel, and was dubious when the transverse hypothesis was asserted publicly in 1821. See Bernard Maitte, La Lumière (Paris: Le Seuil, 1981), 235–236.

² - When John Herschel presented circular polarization, he paid tribute both to Biot, who “has analysed the phenomena with particular care, and it is from his Memoire [. . .] that we extract the following statements,” and to Fresnel whose researches “have been directed to the rotary phenomena with the same brilliant a success which has distinguished his other inquiries into the nature of light.” See John Herschel, Encyclopædia Metropolitana; or, Universal Dictionary of Knowledge, “Mixed Sciences,” Volume II (London: Baldwin and Cradock, Paternoster Row, 1830), 550–551.


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path, is described and explained by comparing its characteristics to those of rays doubly refracted by Iceland spar. All of Malus’s subsequent research attempted to calculate the changes in intensity of light rays when polarized, whether by reflection or by double refraction. Of necessity, Malus held a corpuscular theory of light, polarization then being explained by an orientation of the poles, or axes, of the molecules that make up light, a completely polarized beam being formed of molecules with identically oriented poles. This conceptualization of polarization reached its limit in the study of the general case of a partially polarized beam, where the changes in intensity still reach a minimum, but a non-zero one.

Within the corpuscular theory framework, this beam might be partly composed of completely polarized light (the remainder still being in its natural state), or alternatively, its composition might be explained as a combination of rays polarized in differently oriented planes. And here we reach the limit of explanatory power. In 1811, at this stage of its development, the corpuscular theory was in the ascendency, both as a result of the above scientific context and, as Malus and Arago noted, because it was not known how to place the rival wave theory on a sound mathematical footing. We

5 - Maitte, op. cit. in n. 1, 204–206.
6 - Initially, Malus considered only completely polarized rays, i.e., those with zero light intensity in an orientation perpendicular to their path. This happens only for a specific angle of incidence; it is however an intrinsic property of light rays refracted by crystals. At the same time, careful measurement led Malus, following René-Just Haüy in 1788 and William Hyde Wollaston in 1802, to confirm that Christiaan Huygens’s results regarding the paths taken by rays which were twice refracted by Iceland spar were more accurate than those of Newton. See Étienne-Louis Malus, “Théorie de la double réfraction,” in Mémoires présentés à l’Institut . . . par divers savans II (Paris: Baudouin, 1811), 499, 502–503.
8 - His polarization research results led Malus to reconsider his early work on light and made him rely on the corpuscular hypothesis, which resulted in a greater conceptual unity. See André Chappert, Étienne-Louis Malus et la théorie corpusculaire de la lumière (Paris: Vrin, 1977), 169.
9 - This is Malus’s conclusion from analyzing refraction by an isotropic thick lamina, where the light is only partially polarized, whereas the geometry results in the reflected light being completely polarized. Étienne-Louis Malus, “Sur de nouveaux phénomènes d’optique,” Mémoires de la classe des sciences mathématiques et physiques XI (1811), 108.

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should also add that the work of Malus dealt only with the intensity of polarized “white” beams—the rays corresponding to the various colors making up white light all have the same polarization properties. While Arago was investigating the effect of polarization on colored ring formation, he thus only had available the (very general) definition of polarization and Malus’s Law of Intensity.

The Work of Arago

In 1810–1811, Arago, who was angry with Biot, was charged by the Bureau des Longitudes [Bureau of Longitude] with verifying the proper conformation of the glasses used in telescope construction. Curvature control was achieved by forming Newton’s rings. Additionally, Arago’s duties led him to make many astronomical observations using Rochon prisms to measure the size or distance of celestial bodies. Arago was familiar with the phenomenon of double refraction and, since the two moved in the same circles, he was also knowledgeable about the work of Malus. The latter’s work shows that a completely polarized beam of light can be totally refracted, with no reflection taking place. How does this influence the formation of colored rings? Can the properties of polarized light be used to improve the construction of objective lenses?

Arago soon found that polarized light does not always produce colored rings; its state of polarization may override the geometric conditions leading to their formation. Thus, the Theory of Fits,

13 - First constructed in 1777, this birefringent device slid within the body of the telescope. It was improved in 1784 and was adopted for all lenses, whether moving or fixed. Danielle Fauque, “Alexis-Marie Rochon (1741–1817), savant astronome et opticien,” Revue d’Histoire des Sciences 38, no. 1 (1985): 27 and 33.
14 - A series of measurements was carried out between May 30, 1810, and December 30, 1813. Arago, “Mesures micrométriques faites à la lunette prismatique,” ms. E3 4–5 (Paris, bibliothèque de l’Observatoire).
15 - In general, Laplace considered that it was essential to develop scientific apparatus for verifying hypotheses.
16 - When a corpuscle of light enters the medium of a thin lamina, it causes vibration in an ether. The generated wave propagates faster than the corpuscle. When the latter arrives at the second surface of the lamina, it is transmitted if the wave is easily refracted, otherwise it is reflected. The wave by periodic intervals of easy transmission and easy reflection, controls the action on the corpuscle. By assigning a different access length according to the color which a particle is supposed to produce, we can explain the
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developed by Newton to explain colored rings, is found wanting.\textsuperscript{17} Between 1806 and 1810, Arago carried out measurements which showed, much to the embarrassment of Laplacian scientists, that the speed of light was a constant,\textsuperscript{18} irrespective of any relative motion of the observer and the source. This also cast doubt on the corpuscular theory.

At that time, he had begun the study of the colors caused by polarized light passing through thin sheets of mica,\textsuperscript{19} but did not record this because it implied a relationship—between thickness and color produced by the mica sheet—which was not verified by measurement. Pierre-Simon Laplace and the Academicians condemned such scientific practice and the anticipated verification would never develop as wished.\textsuperscript{20} What did Arago observe and what did he understand?

After passing through a thin sheet of mica, polarized light colors the two images of the birefringent analyzer (for example a Rochon Double Image Micrometer) with complementary colors (since their overlap is always pure white, irrespective of the thickness of the sheets or their inclination) and this is what is known as chromatic polarization.\textsuperscript{21} Verifying that this is not some dispersive effect, Arago then associates this complementarity of color with Newton’s rings. But, in rotating either the sheet in its own plane or the analyzer, for any angle of incidence each image “runs successively and repeatedly through the whole series of prismatic colors”.\textsuperscript{22} This succession of colors, which occurs four times, sometimes

\begin{flushleft}
\textsuperscript{17} François Arago, “Mémoire sur les couleurs des lames minces,” in op. cit. in n. 4, III (1817), 247. Read at the Institute Feb. 18, 1811.
\textsuperscript{18} Jean Eisenstaedt, Avant Einstein (Paris: Le Seuil, 2005), 198. These surprising results will only be published in 1853 by Arago.
\textsuperscript{19} Arago had read Robert Hooke who used them to produce colors.
\textsuperscript{21} The thickness must not exceed 0.45 mm, otherwise the images are not colored.
\textsuperscript{22} François Arago, “Mémoire sur une modification remarquable qu’éprouvent les rayons lumineux dans leur passage à travers certains corps diaphanes, et sur quelques autres nouveaux phénomènes d’optique,” in op. cit. in n. 9, XII (1812), 7. Pagination is irregular.
\end{flushleft}
Frédéric LECLERCQ

in retrograde order, depends on the position of the “axis of the sheet,” and this distinguishes the new phenomenon from that of Newton’s rings whose colors vary only, and in a uniform way, with changes in thickness. With no other analogy observed between the two phenomena, and not having any concepts other than those inherited from Malus, Arago proposed a corpuscular interpretation: crystal plates “depolarize” the incident polarized light depending on the plate thickness. Thus at various thicknesses “molecules of various colors exist whose axes have different directions”.

He gave no measurement, offered no relationship between thickness and color; he had no theory and tried to find out whether the same phenomenon was produced by other crystals. Substituting the mica sheet with one of gypsum, he observed similar phenomena whose colors also depended on the position of the “axis of the crystal.” What was observed with plates of rock crystal, this time of a thickness of several millimeters and cut perpendicular to their axis? Polarized light passing through them along the “axis of the crystal” did not split—quartz apparently has no significant birefringence in this direction—yet, when analyzed, gives rise to color and polarization phenomena. Rotating the plate does not alter the colors in the image analyzer in any way (unlike that which had been found for previous sheets) and, during a complete rotation of the analyzer spar, the two images remain complementary but twice run though the full gamut of prismatic colors—these are the characteristics of circular polarization.

On emerging from the quartz plate, the light is white because, according to Arago, the different colored molecules that compose it “have their poles oriented towards different points in space,” thus the analyzer decomposes this light into two images of

23 - With a biaxial crystal such as mica, the angle of incidence and the orientation of the plane of the sheet cause changes in the amount and the sign of birefringence, hence in the variation and the order of succession of colors.
24 - It is the arrangement that explains birefringence taking a minimum, rather than being zero. In uniaxial crystals, this is indeed the optical axis.
25 - Arago, art. cit. in n. 22, 7. A polarized ray, which partly or totally loses its polarization, i.e., some of whose molecules change orientation, undergoes “depolarization”—a term introduced by Malus.
26 - That is, their optical and their crystallographic axis. (For quartz the optical axis is also the crystallographic axis.)
27 - Arago, art. cit. in n. 22, 117.
28 - Arago, art. cit. in n. 22, 122.
complementary color and intensity. To confirm the influence of thickness on color, Arago had lenses (quartz sheets cut perpendicular to their optical axis) of various thicknesses made. These, when polarized light was shone on them, generated two sets of rings for analysis.  

He concluded that this phenomenon, like the other, “depends on the depolarization encountered by differently colored rays traversing different thicknesses.” Again, there was a link between thickness and color.

While the position of the “axis of the crystal” affects the chromatic polarization of mica and gypsum, the same is not true for the circular polarization of quartz, where a rotation of the sheets has no effect. One may even doubt that color and polarization phenomena occur only in crystals since some parts of flint glass plates, a non-crystalline material, exhibit coloration when illuminated with polarized light.  

Arago did not present his observations accompanied by measurements in the Laplacian style, perhaps because he doubted the foundations of the corpuscular theory—and launched himself into speculation.

For Arago, the colors derive from the structure of the crystals, a superposition of the birefringent lamellae separated by interstices in which partial reflections take place. All of this is qualitative and, as for theory, he concludes that “I propose to call these new rays ‘colored-axis rays,’ to distinguish them from those which have been polarized by reflection or passage through a birefringent crystal. Those, by way of contrast, might be termed ‘white-axis rays.’” At the zenith of Laplacian science, this conclusion is somewhat regressive since the “colored-axis rays” are presented as a type of “polarized ray.”

29 - These were undoubtedly the same monochromatic rings that David Brewster had found in convergent light. David Brewster, Treatise on New Philosophical Instruments (Edinburgh, 1813), 336. In “Sur les lois générales de la double réfraction et de la polarisation dans les corps régulièrement cristallisés,” Mémoires de l’Académie royale des sciences de Paris, III (1820), 196, Biot asserts that Arago is the first to observe this kind of figure.

30 - Arago, art. cit. in n. 22, 127.

31 - Arago, art. cit. in n. 22, 124. Note that this is an accidental polarization due to the glass having been quenched, whether or not intentionally.

32 - Arago, “Mémoire sur plusieurs nouveaux phénomènes d’optique,” in op. cit. in n. 20, X, 89. Read on December 14, 1812.

The Work of Biot

Informed by the observations of his rival, Biot undertook the study of chromatic and circular polarization within a Laplacian framework. Having made hundreds of observations using specially designed apparatus—a repeating circle was adapted to measure various angles, and Robert-Aglaé Cauchoix built a spherometer to determine the thickness of the crystalline laminae to within 0.226 microns. Biot established a numerical relationship between chromatic polarization colors and those of Newton’s rings, namely that, for a color produced by both, there is a constant ratio between the thicknesses of the sheets at the origin of the colors. An experimental law is given in analytical terms, which also holds for perpendicular incidence, provided that the “axis of the crystal” is in the plane of the sheets used. However, varying the angle of inclination (which had made Arago’s research less productive) resulted in more or less complex color variation, depending on the type of sheets used. Experimental laws multiplied, splitting into color laws and intensity laws. In comparison to Arago, Biot understood the specificity of the orientation known as “axis of the crystal or of the sheet” and quickly advanced a mechanical representation of chromatic polarization, that of a pole shift in the light-emitting molecules due to the forces emanating from this axis. The characteristics of this vibration, operating on both sides of the axis, allows the observed chromatic polarization colors to be reproduced, and the laws that codify these form his theory of “mobile polarization,” an extension of the Theory of Fits.

When studying circular polarization, Biot adopted the same approach, but no analytical law linked color to the quartz sheet

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34 - Depending on the birefringence, crystal thicknesses from 20 to 1,000 times greater than an isotropic lamella are required.

35 - Jean-Baptiste Biot, “Sur de nouveaux rapports qui existent entre la réflexion et la polarisation de la lumière des corps cristallisés,” in op. cit. in n. 9, XII (1812), 149.

36 - It should be described by a differential equation whose solution analytically expresses the force exerted on the light by matter. The equation Biot obtained provides no information on this force.

37 - He refined and improved it until the 1816 publication of Traité de physique. Its description appeared on December 27, 1813, with the memorandum “Sur une nouvelle application de la Théorie des oscillations de la lumière,” in op. cit. in n. 9, XIII (1816), 4.

38 - This alternative mechanical movement agrees well with the supposed access alternations of light.
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thickness, because there are no analogous observations between it and the well-understood colored rings. An impasse had been reached; Biot strove to understand the reasons for this setback. He advanced two: on the one hand, he suspected that the analyzer spar does not act on the light coming from the quartz in accord with Malus's Law of intensity. On the other hand, further thought led him to conjecture that the light molecules must perform a continuous circular motion around their center of gravity, while moving along the quartz crystal axis, in a way related to the color corresponding to a molecule. In the latter case, no previous work on color can be associated with this type of movement because, according to Biot, “it is clear that Newton’s table, formed on the basis of alternations in access to reflection and transmission, can no longer serve us in the present circumstances, where it is a matter of calculating the effects of continuous movement.” Consequently, we must first determine how quartz rotates the plane of polarization of each spectral color. In 1813, Biot was of the opinion that only monochromatic light studies could provide clear-cut answers—such studies were not carried out until 1816–1817.

Since characterization of color is delicate, Biot worked with white light and made observations through a glass which only transmitted a near-monochromatic red light. In this way, he determined the rotation of the plane of polarization of a ray of that color as a function of the thickness of the quartz crystal, the angular value of which served as a reference point. But how could the degree of rotation of the other spectral colors be determined?

39 - This study focuses on thirteen different thicknesses of the same plate as it was gradually thinned from 13.416 mm to 0.4 mm. As the thickness decreased, the colors changed in an irregular way from the fourth to the first order.
Although copious measurements were made and always recorded in great detail in Biot’s memoirs, the experimental law—one of great importance—of circular polarization was contained in two lines with no accompanying mathematical apparatus. This law said only that the polarization plane rotations of different elementary rays are “reciprocally proportional to the squares of the access lengths.” In deducing this, he summarized in a table (see Figure 1) and calculated from their corresponding access lengths the eight values of the arc of rotation, per millimeter of quartz traversed, for the elementary rays bordering the seven spectral colors as defined by Newton. To validate this, Biot recovered, by calculation, the color of the observations made in 1812 using white light with thirteen sheets of different thicknesses. The plane of polarization

Figure 1: Arc of rotation of the different elementary rays through a millimeter of rock crystal
(Source: Jean-Baptiste Biot, Sur les rotations que certaines substances impriment aux axes de polarisation des rayons lumineux, Mémoires de l’Académie royale des sciences, II (1819), 58.)

45 - Biot, “Sur les rotations,” 49. The access length is a quarter of the wavelength.
46 - These lengths derive from the work of Newton on colored rings. Jean-Baptiste Biot, Traité de physique, IV (Paris: Deterville, 1816), 109. Recall that the only measurements made by Biot were obtained using red glass.
47 - The boundaries of the seven fundamental colors come from an analogy between notes and colors. Dorothée Devaux and Bernard Maitte, “Newton, les couleurs et la musique,” Alliage 59 (2006): 128.
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of each elementary ray being rotated by an angle depending on its color and the thickness of quartz traversed, one determines by means of Malus’s Law$^{48}$ the light distribution associated with each of the seven colors of the chromatic circle$^{49}$ (see Figure 2) in each image, and then calculates their mixture. Biot, who had already presented the calculation of a mixture of colors in his 1816 *Traité de physique* [Treatise on Physics], recovered not only the colors displayed by each of the thirteen sheets within the limits of visual acuity, but also the intensities of the two images of the analyzer. Although this study of circular polarization showed a disjunction with chromatic polarization, the introduction of measurements and the use of methods inherited from Newton maintained the coherence of corpuscular theory.

The law of rotation of the polarization plane was successfully applied to other crystals, but none of these measurements and

$^{48}$ - This new work allays Biot’s suspicions about the limits of applicability of this law and, in turn, confirms its universality.

$^{49}$ - This ad hoc figure arises from the same analogy. Devaux and Maitte, op. cit. in n. 47, 135.
Observations were accompanied by any interpretation. Biot offered no mechanical justification—there is no reference to the rotational motion of the light molecules—and did not even mention the nature of light, but he extended his research to liquids, which put his theory to a new test.\textsuperscript{50} Liquids behave similarly to quartz; the law of rotation already defined seems general, exceptionless. Only the intensity and the direction—levorotation or dextrorotation—differ depending on the liquid,\textsuperscript{51} or from one quartz sample to another. One may easily calculate the action resulting from a mixture of several liquids, as long as they are mutually inert. In short, Biot was convinced that the light, having undergone a rotational action of polarization by material bodies, and by fluids in particular, had been affected by a simple property of matter.\textsuperscript{52}

Here, we may be seeing one of the most basic actions performed by any assemblage of matter. Soon, Fresnel will have Biot’s results available to him before they are made public.\textsuperscript{53}

**The Work of Fresnel**

Fresnel believed that heat and light were the vibrational manifestations of a specific fluid and did not believe that the corpuscular theory of light was valid—Newton was turning in his grave.\textsuperscript{54}

Having no knowledge of the interference principle, stated but not made widely publicized by Thomas Young,\textsuperscript{55} he began building the

\textsuperscript{50} In particular, turpentine in its liquid and vapor state.

\textsuperscript{51} Biot determined the intensity of their action by neutralizing the opposing effects of different bodies.

\textsuperscript{52} Biot, art. cit. in n. 44, 42.

\textsuperscript{53} Biot read his research in September 1818; it was published in two books of the *Annales de chimie et de physique* at the end of 1818 and early in 1819 (Vols. IX and X). Fresnel reported his research on the colors developed by fluids from March 1818 onward.

\textsuperscript{54} Maitte, op. cit. in n. 1, 221.

\textsuperscript{55} He did not build a wave theory that was well founded on the interference principle—as he himself was the first to admit—because he did not enunciate a mathematical theory that included all the geometric conditions from which one observes phenomena. In 1815, when he failed to apply the principle of interference to polarization phenomena, Young recounted his confusion to Brewster (see *Miscellaneous Works of the late Thomas Young* [London: John Murray, 1855], I, 361). Young’s work was universally rejected. In England, Henry Brougham, one of the most influential contemporary scholars because of his writings in the Edinburgh Review, displayed only sarcasm towards his compatriot’s work and denied that Young—erroneously considered a poor experimenter—might hypothesize the existence of an ether that no induction could subsequently demonstrate, but accepted it when introduced by Newton as that was a conjecture arising from, and then confirmed by, experience; “Geoffrey Cantor, Henry Brougham and the Scottish methodological tradition,” *Studies in History and
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foundations of wave optics without having read either Newton or Huygens.\textsuperscript{56}

Arago, who also doubted the value of the corpuscular theory, and who disagreed with Biot,\textsuperscript{57} aided Fresnel as much as he could in developing wave theory. The journal \textit{Annales de chimie et de physique} [Annals of Chemistry and Physics], which he founded in 1816 with Louis-Joseph Gay-Lussac served as a forum for the dissemination of this new theory. It was a powerful lever to counter the influence of the Institute which favored the Newtonian party.

As early as October 1815, Fresnel presented his first memoir on diffraction although his explanation of the causes of the phenomenon—reflection of light on the edges of the screen—was wrong. Applying the principle of interference did explain the hyperbolic shape of the fringes well,\textsuperscript{58} but their predicted location differed somewhat from that observed. Fresnel went on to improve his memoir, subsequently “crowned” by the Institute in 1819, by extending the principle of Huygens. With diffraction, the physical character of the waves in the ether that constitute light is unimportant; but this does not seem to be the case with polarization phenomena.

Thus, Fresnel and Arago attempted to explain chromatic polarization. Results arrived thick and fast\textsuperscript{59}—in August 1816, calculations using Malus’s results for thick crystals confirmed that the observed colors were related to the difference in speed between the ordinary (O) and extraordinary (E) rays.\textsuperscript{60} These results contradicted Biot, who had distinguished between chromatic polarization due

\textit{Philosophy of Science} 2, no. 1 (1971): 87. In France, scientists of the Institute had no respect for theories without a mathematical foundation.

\textsuperscript{56} - Maitte, op. cit. in n. 1, 220–222.
\textsuperscript{58} - Augustin Fresnel, “Premier mémoire sur la diffraction,” in op. cit. in n. 1 (1866), 23.
\textsuperscript{59} - Initially, Fresnel’s scientific activity was punctuated by leaves spent in Paris, where he continuously met Arago. The first leave extended from February 1816 to the end of this year, and the second occurred during the autumn of 1817. Fresnel resided permanently in the capital from May 1818. See Émile Verdet, “Introduction aux œuvres d’Augustin Fresnel,” in op. cit. in n. 1 (1866), xxx–xxx.
\textsuperscript{60} - Augustin Fresnel, “Mémoire sur l’influence de la polarisation . . . ,” in op. cit. in n. 1 (1866), 394–396.
to thin laminae and birefringence due to thick plates. These rays cannot spontaneously interfere, being polarized in “contrary directions” to each other, but superimposition does occur if their polarization planes form any angle, other than 90°, with the planes of the lamina’s principal section and of the analyzer, a situation which Fresnel and Arago succeeded in explaining. This study already renders the transverse nature of these waves analytically more likely. However, this property is only asserted in 1821 in order to avoid the difficult question of the mechanical definition of the ether.

Towards the end of 1817, we may consider the theory of diffraction as nearing completion and that of chromatic polarization as being well advanced. Only one question, albeit an important one, that of the nature of the waves, interfered with this picture of light. Around this time, Fresnel was working simultaneously on all these questions. The advanced status of polarization color calculation allowed Fresnel to predict, when two crystal laminae were combined, color variations that had escaped Biot’s observation, even though he was an excellent experimentalist. Fresnel had to explain circular polarization in order to demonstrate that the principle of interference was truly universal—after that he would be able to formulate his theory of the nature of light. First, he faced a major obstacle. The principle of interference depended on the difference of velocities of two kinds of rays, the ordinary (O) and the extraordinary (E), in polarization phenomena. But, as Arago first noted, colors are observed in circular polarization without any double refraction. How might Fresnel apply the principle of interference? If Arago and Biot had largely reconciled both color polarizations, Fresnel needed to truly

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61 - The theory of mobile polarization explained the colors of chromatic polarization while fixed polarization corresponded to double refraction. The main drawback of this theory was that Biot did not know how to justify oscillations ceasing at a certain thickness (about 0.45 mm) of a crystalline lamina where there was a loss of coloration.

62 - Fresnel, op. cit. in n. 1 (1866), 399. This clearly goes beyond Young, as Fresnel proves the prior necessity of polarized light.


64 - In June, just before the controversy with Biot on mobile polarization. *Annales de chimie et de physique* XVII (1821), 179.

65 - Augustin Fresnel, “Supplément au Mémoire sur les modifications que la réflexion imprime à la lumière polarisée,” in op. cit. in n. 1 (1866), 487.

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unify the two phenomena to avoid this serious issue. Two observations formed the basis of his future success, one regarding the reflection of polarized light, the other on the colors in chromatic polarization.

In November 1817, Fresnel observed that the rotation of a reflecting surface resulted in the reflected light being polarized; this led him to a new train of thought. He noticed that two total reflections of polarized light within a glass parallelepiped completely depolarize it. This depolarized light leaves the intensity of images in the analyzer unchanged, as though it were natural light, but it clearly is not, since it produces complementary color images when passed through a sheet of gypsum. Above all, Fresnel found that, by laying out these colors on Newton’s color wheel (see Figure 2), they were definitely different from those produced by polarized light, but intermediate to them, a quarter turn on the wheel away from the former. By analogy, this observation led Fresnel to the structure of the depolarized wavelength.

Regarding circular polarization, the crux of the matter was to combine the action of the parallelepipeds that converted polarized and depolarized light. The experimental device Fresnel used to reproduce circular or liquid polarization was a pair of parallelepipeds flanking a thin sheet of gypsum (see Fig 3). Rotating this grouping $P1-L-P2$ resulted in no perceptible color changes, such as would be caused by quartz or a tube of turpentine, but rotating the analyzer $A$ by itself resulted in a succession of colors similar to those from quartz. Had Fresnel discovered the optical circular polarization model? We do not have space to elaborate on the vacillations and setbacks that arose from a methodology in which experiment and theory were so tightly interlinked. So, for the sake of clarity, we will separate experimental research from its theoretical counterpart, taking care to distort neither.

67 - Augustin Fresnel, “Mémoire sur les modifications que la réflexion imprime à la lumière polarisée,” in op. cit. in n. 1 (1866), 442–443. This property had escaped Malus and Biot.
68 - Fresnel, op. cit. in n. 1 (1866), 454. This is a process which transforms linear into circular polarization, and vice versa.
69 - Formed of two waves of equal intensity polarized in perpendicular planes, one retarded by a quarter wavelength relative to the other.
70 - Fresnel, op. cit. in n. 1 (1866), 460.
The measurements were carried out using the device in Figure 4—polarized light passed through turpentine, then through parallelepiped $P_1$ before being analyzed. This light then had all the characteristics of chromatic polarization; its color could be compensated by a gypsum sheet.\(^1\) And indeed, on inserting a sheet of suitable thickness between $P_1$ and $A$,\(^2\) one of the images of the analyzer could be zeroed out by rotating the main section of the parallelepiped $P_1$ through an angle $r$. The value of $r$ permitted the experimental determination of the rotation produced by turpentine on a specific color. Fresnel’s measurements corresponded to those of Biot, who, impressed, transposed them to the case of quartz, appended them to his own memoir (see Figure 5) and concluded that “Mr. Fresnel has discovered the connecting knot between the two classes of phenomena . . .”\(^3\) However, this was still insufficient, because the results could only be found by calculation.

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\(^{1}\) - Augustin Fresnel, “Mémoire sur les couleurs développées dans des fluides homogènes,” in op. cit. in n. 1 (1866), 660–661. On traversing a crystalline lamina, two kinds of polarized rays having different speeds emerge, resulting in colors being produced. If these rays pass through another lamina of the same crystal, whose axis is rotated through $90^\circ$, they exchange their roles. Consequently, the speed difference changes sign when traversing the second crystal. For identical thicknesses, there is exact compensation between the speeds and consequent disappearance of the colors. This procedure is due to Biot who gave a different explanation within a corpuscular framework. Thus, the conjunction of the liquid followed by the parallelepiped behaves like a crystal lamina.

\(^{2}\) - To complete the measurement, it is necessary to adjust the length of the tube of turpentine.

\(^{3}\) - Biot, art. cit. in n. 44, 134. Arago and Biot act as rapporteurs for Fresnel’s memoir.
Arago, Biot, and Fresnel Elucidate Circular Polarization

**Figure 4**

P: polarizing device; A: birefringent analyzer

T: tube filled with essence of turpentine; P1: polarizing parallelepiped

r: angle between the plane of polarization of P1 and the original plane P

i: angle between the principal section of A and the original plane P

<table>
<thead>
<tr>
<th>Color</th>
<th>Observation</th>
<th>Mr. Fresnel’s formula</th>
<th>Over-calculation by the formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium red</td>
<td>18° 9881</td>
<td>18° 988 1</td>
<td>+0°.000 0</td>
</tr>
<tr>
<td>Orange</td>
<td>21.396 8</td>
<td>21.510 5</td>
<td>+0.113 7</td>
</tr>
<tr>
<td>Yellow</td>
<td>23.994 5</td>
<td>23.962 8</td>
<td>−0.031 7</td>
</tr>
<tr>
<td>Green</td>
<td>27.860 6</td>
<td>27.396 0</td>
<td>−0.464 6</td>
</tr>
<tr>
<td>Blue</td>
<td>32.308 8</td>
<td>31.109 7</td>
<td>−1.199 1</td>
</tr>
<tr>
<td>Indigo</td>
<td>36.127 6</td>
<td>34.122 5</td>
<td>−2.004 8</td>
</tr>
<tr>
<td>Violet</td>
<td>40.882 8</td>
<td>37.486 0</td>
<td>−3.4</td>
</tr>
</tbody>
</table>

**Figure 5**

The colors are those which correspond to the middle of the intervals considered by Biot in Figure 1 above—this explains the differences.

(Source: Jean-Baptiste Biot, “Sur les rotations que certaines substances impriment aux axes de polarisation des rayons lumineux,” Mémoires de l’Académie royale des sciences, II [1819], 135.)
Initially, Fresnel was less happy in the application of the interference principle. Replacing essence of turpentine by the apparatus described above and then calculating the rotational power of quartz or liquids resulted in “an angle more than double that which M. Biot had determined by direct measurement, and which he was so kind as to communicate [to me].” Following this setback, Fresnel reconsidered the action of essence of turpentine and assumed that light traversing it was acted upon by a succession of elementary cells each rotated at an identical angle from its predecessor, and formed as the apparatus described (two parallelepipeds flanking a gypsum sheet).

Then the calculation showed that a polarized monochromatic ray has its plane of polarization rotated by an angle which is related to its path length through the liquid, this being consistent with Biot’s observations. This theoretical result, however, implies a disturbing consequence, one which yields many insights. The deduced rotation of the polarization plane depends on the birefringence of gypsum (which is almost constant across the spectrum), and hence is almost insensible to the color of the light. This, of course is contrary to the observations made by Biot. However, this application of the interference principle allowed the confirmation of Fresnel’s measurements (see Figure 5). The analytical relationships indicate that rotating $P1$ by an angle \( r \) (see Figure 4), neutralizes the gypsum birefringence, which explains the color compensation by the experimental method described above.

Fresnel had reached the goal he set himself, that of creating a theory that had “the advantage of explaining the color produced in polarized light by homogeneous fluids, by the same principles as used for crystalline laminae . . .” Additionally, his work suggested a new birefringence whose existence needed to be proven by observation. In 1822, Fresnel designed, as suggested by his theory, a montage of two quartz prisms, one levorotary, the other dextro-rotary, whose angles were based on a calculation. Observation confirmed that the completely polarized incident ray undergoes

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74 - Fresnel, op. cit. in n. 1 (1866), 662. This calculation cannot be found.
75 - Fresnel, op. cit. in n. 1 (1866), 680.
76 - Fresnel, op. cit. in n. 1 (1866), 738.
Arago, Biot, and Fresnel Elucidate Circular Polarization

A (very weak)\textsuperscript{77} double refraction—whose rays are then further divided by the other type of quartz. The circular birefringence of quartz was exerted on a linearly polarized beam, while a circularly polarized (depolarized) ray, underwent only simple refraction.\textsuperscript{78} The latter polarization could be regarded as a combination of linear polarizations as Fresnel had originally assumed (see Note 69). With the discovery of circular birefringence, Fresnel extended the concept of polarization, gave the interference principle an unequivocal generality, and endowed wave theory with a flawless consistency.

Long after the work of Fresnel had been acknowledged, Arago’s memoirs from 1811 and other years were published in his Œuvres complètes [Complete Works], which appeared from 1853 onwards. We find in Note 22, retained verbatim but renamed Mémoire sur la polarisation colorée [Memoir on Colored Polarization],\textsuperscript{79} the very general principle of depolarization as an explanation of chromatic and polarization rotation, while the conceptualization of the notion of polarization in wave theory allowed the most exact justifications of these properties of light. In Volume VII of the Œuvres complètes, depolarization (Chapter VIII), colored polarization (Chapters X and XI) and an overview of polarization phenomena lack any mathematical apparatus, have almost no measurements, and are uncertain as to the nature of light. Although the deficiencies of the corpuscular theory were almost universally accepted by 1850, there was little willingness to accept transverse waves in the ether as a model for light.\textsuperscript{80} Arago was well aware of the difficulties that accompanied the two theories of light thanks to his functions as perpetual secretary of the Academy of Sciences,\textsuperscript{81} but he did not renounce his earlier research and passed on what he knew (a lot, having worked on many and diverse subjects), regardless of the “absolute” relevance of this knowledge.

\textsuperscript{77} - It is precisely estimated to almost one part in one million. Fresnel, op. cit. in n. 1 (1866), 664.

\textsuperscript{78} - Augustin Fresnel, “Mémoire sur la double réfraction particulièrer que présente le cristal de roche dans la direction de son axe,” in op. cit. in n. 1 (1866), 744. Also published in Bulletin de la Société Philomathique for 1822.

\textsuperscript{79} - We were unable to ascertain exactly when Arago changed title. This characterization of polarization appeared as early as 1812. Arago, op. cit. in n. 20, X, 96.

\textsuperscript{80} - In 1851, Arago refused to write for the Academy the introduction to a note on interference.

\textsuperscript{81} - Elected in 1830 following Fourier whom he had implicitly supported over Biot in 1822.
Besides the fact that Biot was the first to state the experimental law of circular polarization, his studies were cutting-edge, including, as they did, accurate measurements allowing the establishment of experimental laws relating to a mechanical movement, that of a molecule of light in the role of a test body. The solution of its differential equation must describe the force exerted on light by the constituents of matter. This proved sterile for the oscillations representing chromatic polarization—it was not possible to associate such an equation with circular polarization. Too ambitious in its descriptions, Laplacian science had reached its limits when applied to polarization and color phenomena. Biot passed on to posterity his experimental work and laws whose value is based on those of Newton. Although satisfied that circular polarization by liquids was the most direct manifestation of the action of matter on light,\(^{82}\) new studies undertaken from 1832 did not add to the corpuscular theory of light, but were closer to optics, chemistry, and crystallography. Biot remains one of the architects of a science aspiring to universality.

In 1818, Fresnel strengthened wave theory with his study of circular polarization, undoubtedly even more than he had by his diffraction studies. He did this by using a different experimental method to recreate Biot’s results, and by justifying them with the interference principle. Biot, rapporteur at the Institute where Fresnel worked, noted that they had made more progress with this theory than with diffraction. Although in 1818, Fresnel suspended work on polarization phenomena in order to complete his diffraction memoir, he knew they were well developed enough to engage, in 1821 at the Institute, in a controversy about mobile polarization, highlighting the shortcomings of that theory. Biot could only be on the defensive and, with good reason, divert attention towards the mechanical nature of light. Indeed, how might waves, other than longitudinal ones, propagate in a fluid such as the ether? Simultaneously, Fresnel set out his position on this issue in the *Annales de chimie* [Annals of Chemistry], a more accommodating platform, and proposed a new model of the ether.\(^{83}\) Moreover, the explanation of the birefringence of biaxial crystals further added to wave theory, the discovery of circular birefringence supplementing

\(^{82}\) - Biot, art. cit. in n. 44, 51.
\(^{83}\) - Maitte, op. cit. in n. 1, 236–238.
and completing Fresnel’s research. The latter phenomenon was at the origin of a truly general conceptualization of polarization—whether straight, circular, or elliptical. It reinforced the connecting node that Biot had detected in the work of Fresnel. That, in turn, brought the wave concept to the end of its development, only the nature of the waves remained open to criticism. The interference principle no longer had any exceptions to its application, which gave wave theory a consistency lacking in the theory of corpuscles.