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From Huygens' waves to Einstein's photons: Weird light ☆

Des ondes de Huygens aux photons d'Einstein : une étrange lumière

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A B S T R A C T

From Huygens to Kastler, the members of the Académie des sciences have played an important role in the development and/or the thorough understanding of the models of light. This has paved the way to modern Quantum Optics.

R É S U M É

De Huygens à Kastler, les membres de l'Académie des sciences ont joué un rôle important dans le développement et/ou la compréhension profonde des modèles de la lumière. Ils ont ainsi permis l'émergence de l'optique quantique moderne.

1. Emergence of a wave model of light

In the year 1666, Colbert invited the greatest scientists of the time to join the newly created "Académie des sciences". One of the most eminent of them, Christiaan Huygens, born in 1629 and grown up in the Netherlands, had studied the works of Descartes, Pascal, and Fermat, and already produced major results in mechanics, mathematics and astronomy. He accepted to come and settle in Paris, where he would dwell until Colbert's death and the revocation of the "Édit de Nantes" – events that led him to return to his native land, to spend there the rest of his life.

In 1672, Huygens discovered Newton's work on the corpuscular model of light. At the time, the major problem was to find a model that would justify the laws of reflection and refraction, independently formulated by Descartes and Snell (Fig. 1). It is easy to understand that a bouncing corpuscle is a good model to describe the fact that a ray of light is reflected in a symmetrical way with respect to the normal, but the challenge is to understand why the refracted ray comes closer

☆ This paper is based on a text that was published in the *Lettre de l'Académie des sciences*, as a record of a speech pronounced for the 350th anniversary of the foundation of the Academy, in 2016. It emphasizes the role of the members of the "Académie" in the evolution of the models of light, and extends over a period much broader than the existence of the *Comptes rendus*. Before the creation of the latter, the *Mémoires de l'Académie des sciences*, which can be found on the site Gallica of the "Bibliothèque nationale de France" (French National Library), are an invaluable source of major documents, such as Fresnel's *Mémoire sur la diffraction de la lumière*, published in 1819. The long time it took for an article to be published, however, was a motivation to create the *Comptes rendus*, whose first role was to publish as fast as possible the discoveries presented in the weekly sessions of the "Académie".

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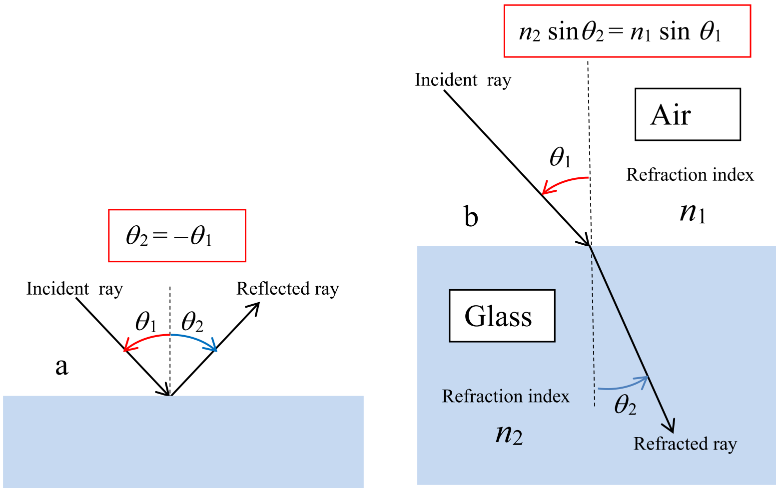


Fig. 1. Christiaan Huygens soon considered the question of light beam reflection and refraction. (a) Reflection: $\theta_2 = -\theta_1$. (b) Refraction: $n_2 \sin\theta_2 = n_1 \sin\theta_1$. Adapted from Josell7 – Own work.

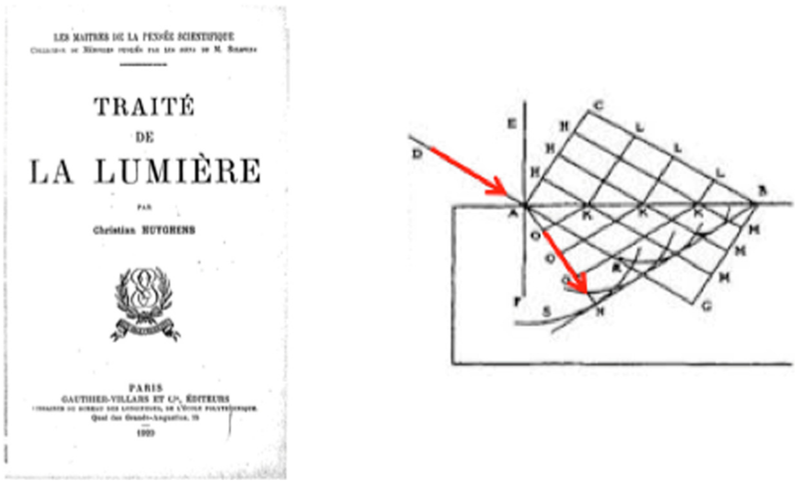


Fig. 2. Huygens' wave model, expressed in 1678 and fully described in 1690, accounts for refraction provided that the speed of light is slower in the denser medium than in air, in contrast to Newton's corpuscular theory.

to the normal when it passes from air to a denser medium, such as water or glass. Newton explained it by invoking the attraction of the denser medium: the particles of light are accelerated perpendicularly to the interface, and the trajectory is therefore closer to normal. But Huygens was looking for a model that would account for all known phenomena, and in particular the phenomenon of double refraction that is observed with some crystals, such as calcite. He discovered in 1678 that a wave model of light would meet this requirement, while Newton's corpuscular model did not. His model could render an account of refraction (Fig. 2), provided that the velocity of light is smaller in the denser medium, i.e., the contrary of Newton's model.

Despite its value, Huygens' wave model, described in full detail in 1690 in his *Treatise on Light*, [1] was ignored by most scientists for more than a century. If they had adopted the corpuscular model, it was because of the tremendous prestige conferred upon Newton, who had managed to explain the motions of planets through his law of universal gravitation. It took more than one century before Thomas Young, in England, and Augustin Fresnel, in France, developed the wave model of light, as the only one able to account for the phenomena of interference and diffraction, that they carefully studied in remarkable experiments (Fig. 3).

2. Wave *vs.* corpuscular theories

Young and Fresnel had to fight to impose this model, as evidenced by the story of Poisson's bright spot, which involved several members of the Académie.

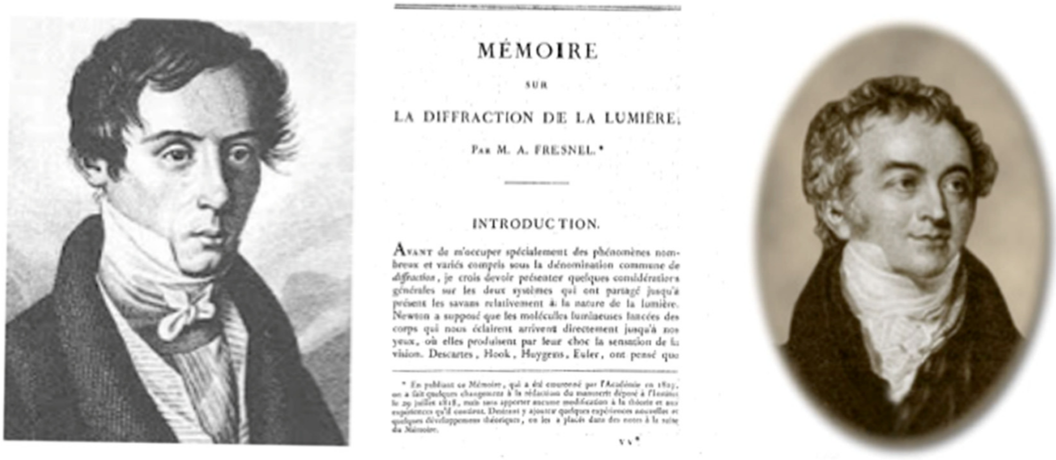


Fig. 3. In France, Augustin Fresnel (1788–1827) developed the wave model in the frame of a contest launched by the "Académie des sciences". In parallel, Thomas Young (1773–1829) conducted his work in England.

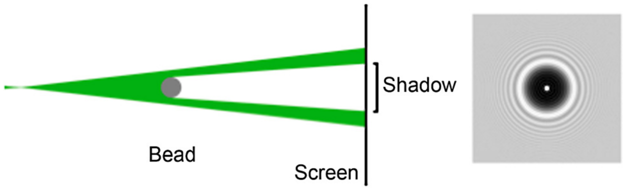


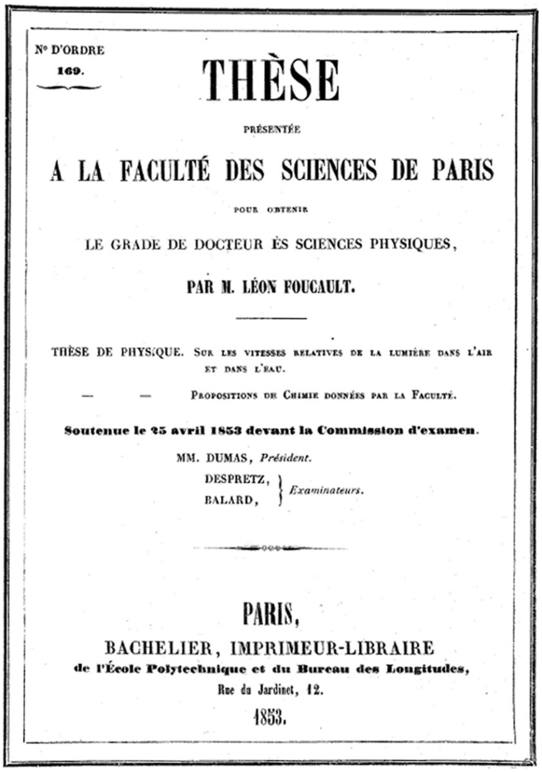
Fig. 4. The Poisson's bright spot: Fresnel's theory predicts the existence of a bright spot in the middle of the shade. The observation of that counterintuitive feature played an important role in the success of Fresnel's wave theory of light.

1819 was the year, and the Académie des sciences had sponsored a contest on the diffraction of light, in other words, on the fact that, in the zone of transition between the shadow of a screen and an illuminated zone, fringes are observed, that is, alternating shadows and light. Fresnel, a young and brilliant mind educated at the "École polytechnique", and who was a student of the academician Arago, presented a memoir [2] describing his experiments and giving a complete mathematical treatment of the problem, based on a convincing wave model. Many members of the "Académie", though, were eminent scientists in mechanics, whose works were based on Newton's mechanics, and they would not admit that Fresnel questioned their hero, even in a field other than mechanics. Siméon Denis Poisson, one of the die-hard Newtonians and a sophisticated mathematician, discovered a surprising consequence of Fresnel's equations: if a light source is placed on the axis of a circular obstacle that blocks light, the theory predicts that there will be a bright spot behind the screen, at a place where common sense tells us that utter darkness reigns (Fig. 4). Does it not show that Fresnel's theory is absurd? This is when the events took a surprising turn that the history of physics still remembers: Arago decided that an experiment should be conducted, and, to the amazement of Poisson and the Newtonians, the bright spot was indeed observed. The story has it that the Académie then shifted in favour of the wave theory, awarding Fresnel the prize of the competition and soon admitting him as a new member [3].

Some historians of science claim that the story has been embellished, and that the conversion to wave theory was far from being so massive. As a matter of fact, as, for example, Dominique Pestre explains it [4], Poisson was dazzled by the elegance and mathematical consistency of Fresnel's theory, and was waiting only to welcome him at the "Académie", while being at the same time not really convinced that Newton's optics should be rejected. One cannot fail to notice, indeed, that the followers of the corpuscular theory remained active in the subsequent years until a new episode would clear the debate. Arago – he again – once more played a key role in 1838, when he proposed a crucial experiment to settle the argument between Newton's corpuscular theory, then called the "system of emission", and Fresnel's wave theory, called the "system of undulations". All it takes, he explained, is a comparison between the speed of light in air and in a refractive medium such as water. One remembers, indeed, that, in Newton's theory, light accelerates when it penetrates a denser medium; on the contrary, according to the wave theory of Huygens and Fresnel, light goes slower in the denser medium (Fig. 2).

In 1849, Fizeau had measured the speed of light between Montmartre and Suresnes, over a distance of 8633 m, and found a value in agreement with the astronomy-based measurements [5]. The website of the "Observatoire de Paris" presents a remarkable description of this experiment, which was repeated in 2005 with a laser beam (Fig. 5). In 1850, Foucault improved the experimental set-up and was able to realize the measurement over a distance of only one meter. He could then directly compare the speed of light in air and water [6]. The thesis (Fig. 6) of the future member of the Academy is only 35 pages long and it plainly concludes: "always, light is delayed as it passes through the most refractive medium. The

Fig. 5. Measurement of the speed of light between the "Observatoire de Paris" and Montmartre, in 2005 (http://expositions.obspm.fr/lumiere2005/tir_pratique.html).



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THÈSE

PRÉSENTÉE

A LA FACULTÉ DES SCIENCES DE PARIS

POUR OBTENIR

LE GRADE DE DOCTEUR ÈS SCIENCES PHYSIQUES,

PAR M. LÉON FOUCAULT.

THÈSE DE PHYSIQUE. Sur les vitesses relatives de la lumière dans l'air et dans l'eau.

— — Propositions de Chimie données par la Faculté.

Soutenue le 25 avril 1853 devant la Commission d'examen.

MM. DUMAS, *Président.*
DESPRETZ, } *Examinateurs.*
BALARD,

PARIS,

BACHELIER, IMPRIMEUR-LIBRAIRE
de l'École Polytechnique et du Bureau des Longitudes,
Rue du Jardinet, 12.

1853.

Fig. 6. *Sur les vitesses relatives de la lumière dans l'air et dans l'eau*. PhD thesis by Léon Foucault, presented to the Paris Faculty of Sciences in 1853 (https://www.bibnum.education.fr/sites/default/files/foucault-texte.pdf).

final conclusion of this work thus consists in declaring the system of emission *incompatible* with the reality of the facts." The last followers of the corpuscular theory then surrendered or passed – is it not a saying that new theories do prevail only when their detractors have passed?

In these times of debate and sometimes opposition between fundamental research and applications, it should be pointed out that the theoretician Augustin Fresnel was also the father of modern lighthouses, which he contributed to conceive as a "Ponts et Chaussées" civil engineer, and which are equipped with the marvellous Fresnel lenses (Fig. 7). As for his theory of wave optics, it is so perfect that we may continue to use it without making any change to it. But in 1818, Fresnel still lacked the answer to this question: what is the nature of this quantity that vibrates as it propagates?

It was the Scottish genius James Clerk Maxwell who gave the answer, in 1864. He had written equations enabling one to describe the whole set of facts that were known at the time in the fields of electricity and magnetism. In any genuine

Fig. 7. A huge Fresnel lens in a lighthouse.

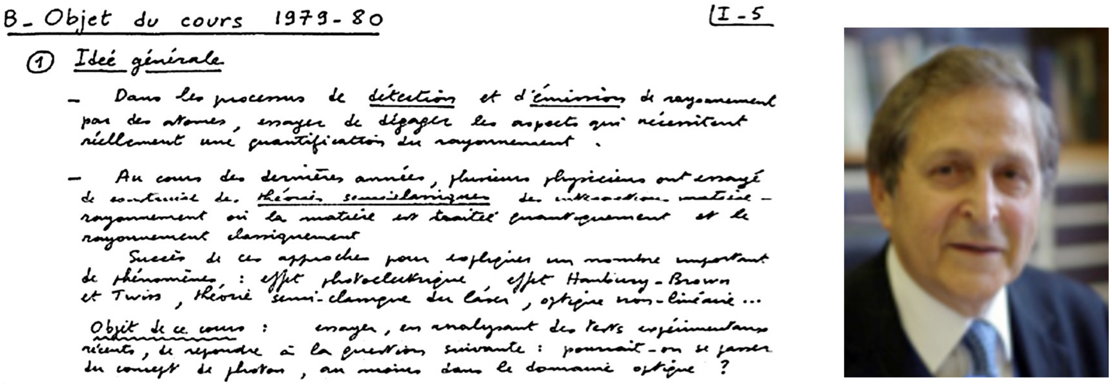
Fig. 8. With Albert Einstein (1879–1955), 1905 marks the revival of the theory of particles, allowing him to make predictions on the photo-electric effect confirmed by experiments of Robert Millikan (1868–1953) in 1915.

physical theory, equations imply more than what has been used to establish them; they have new solutions whose traces may be looked for through experimental observation. In the case of Maxwell's equations, the novelty was impressive: some solutions of the equations indicated waves propagating at a speed that Maxwell calculated. And he concluded: "This speed is so close to that of light that it seems we have good reason to conclude that light itself [...] is an electromagnetic disturbance in the form of waves propagating through the electromagnetic field according to the laws of electromagnetism."

The case thus seems settled: light is now known to be an electromagnetic wave; in other words, electric and magnetic fields vibrating in harmony, perpendicularly to the direction of propagation. That is to say they are transversal waves, as Fresnel's waves, and we can describe these waves with a comprehensive theory to which no phenomenon seems to be able to escape. Is it the end of theoretical research in physics, and is there nothing for physicists but to refine their measurements, as the American experimentalist Michelson reportedly put it? Surely not. In 1900, the great Kelvin caught sight of two "clouds above the dynamical theory of heat and light" [7]. Such two clouds, which Kelvin described as "very dense", would lead Einstein to lay the foundations of the two revolutions of the 20th-century physics: relativity, as is well known, but also quantum physics, in the emergence of which he would play a key role [8].

3. The wave–corpuscle duality

Einstein's first article on quantum physics was published in 1905. It propounds a drastic hypothesis: light is formed of grains, *Lichtquanten*, with well-defined energy and momentum, depending on the constant introduced by Planck in 1900. Today, these quanta of light are called photons. Drawing on this model, Einstein interpreted the photoelectric effect – in other words the ejection of electrons from matter under the effect of light – as a photon–electron collision, and thus deduced what was the energy of the ejected electrons. Among the works that Einstein published in 1905, a golden year, this article was certainly the least appreciated of all, as can be seen from a negative comment in the report that would however lead to his election at the Prussian Academy of Sciences in 1911. Yet it was this article that caught the attention of the Nobel Committee, awarding him the Prize in 1922 after Millikan's experiments confirmed Einstein's predictions on the photoelectric effect – a confirmation "contrary to all my expectations", said Millikan in his memoirs [9] (Fig. 8).


B_ Objet du cours 1979-80 (I-5

① Idée générale

– Dans les processus de détection et d'émission de rayonnement par des atomes, essayer de dégager les aspects qui nécessitent réellement une quantification du rayonnement.

– Au cours des dernières années, plusieurs physiciens ont essayé de construire des théories semiclassiques de l'interaction matière-rayonnement où la matière est traitée quantiquement et le rayonnement classiquement.
Succès de ces approches pour expliquer un nombre important de phénomènes : effet photoélectrique, effet Hanbury-Brown et Twiss, théorie semi-classique du laser, optique non-linéaire...

Objet de ce cours : essayer, en analysant des tests expérimentaux récents, de répondre à la question suivante : pourrait-on se passer du concept de photon, au moins dans le domaine optique ?

Fig. 9. Fruitful questioning: "Object of this course: to try to [...] answer the following question: could we do without the concept of photon, at least in the field of optics?". Claude Cohen-Tannoudji, course at the "Collège de France", 1979.

The corpuscular model was back on track. But then, how could one account for interferences, diffraction or double refraction, as Young and Fresnel showed they could only be consistently explained through the wave model? How could one make this corpuscular model compatible with Maxwell's description of light as an electromagnetic wave? Einstein, an admirer of Maxwell, could not ignore the question and provided a masterful answer to it on his first appearance at a scientific conference, the conference of German physics that was held in Salzburg in 1909. Einstein developed there a series of arguments and concluded: "I only wanted to briefly illustrate the fact that the two structural properties (wave structure and quantum structure) [...] should not be seen as incompatible." At the end of each argument, Einstein's conclusion was the same: light is both wave and corpuscle. It would take fourteen years before Louis de Broglie would express this wave–corpuscle duality, this time not for light, but for material particles [10].

With wave–corpuscle duality, modern quantum physics was born. Optics would continue progressing all over the 20th century, notably with the invention of the laser, and the French scientists, perpetuating the tradition of their predecessors, would take an eminent stand there, supplying the Académie with important battalions. But the wave–corpuscle duality of light still remained quite mysterious, as is apparent from the questions of the future Nobel laureate Alfred Kastler, then a high-school professor in Bordeaux in 1932: "If this synthesis satisfies the mathematician, he wrote, it continues to worry the physicist, who shall not be content with abstract formulas. To him, the duality between the wave aspects and the corpuscle aspects of light remains an unresolved mystery..." [11]. Such questions led him to discover optical pumping with Jean Brossel [12].

Thirty-two years later, as a student in upper sixth at the "Lycée" of Agen, I asked a similar question to my physics teacher who had a hard time to answer it, despite his outstanding capacities. It would take me fifteen more years to find, as many of my contemporaries, illuminating answers in Claude Cohen-Tannoudji's course at the "Collège de France", as he clarified such questions and thus enabled the French School of Quantum Optics to exert a radiant influence throughout the world (Fig. 9).

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