Applying Kuhn's Concept of Scientific Revolutions to the History of Wave-Particle Duality

Beatriz Gietner

May 2024

1 Introduction

In this present essay, I discuss the following:

- What is the nature of light and the discussions developed in such a journey;
- The importance of studying both Philosophy and the History of Science;
- How the works of Thomas Kuhn were essential to a better understanding of how a community of scientists structures itself;
- How some aspects of a scientific revolution can be applied to the wave-particle duality historical period.

2 What is light?

"We know to tell many fictions like to truths, and we know, when we will, to speak what is true."
– Hesiod

Let us say you wake up on a bright Saturday morning and, out of the blue, decide it is a good day to go out and ask people random questions about scientific things. You think valuable sampling is necessary, so you choose O'Connell Street for a start to achieve high numbers and considerably diverse backgrounds. There are loads of people there who do not speak English or even think anything else is better than having to face a cheerful Irish person disturbing their shopping stroll. Regardless, you proceed with your plan to discover what they think is the phenomenon of light and how it is linked to the notion of the atom.

Probably some of them will recall introductory physics and chemistry school lessons and answer that "light is a wave, atoms are the tiniest constituent of matter, no connection between them two," "light is composed of particles, so is the atom," "light allows us to see the world around us and atoms are what we are made made of," or they perhaps even go further and chat over stars, galaxies and the universe (I might be wishful thinking). The point is that the most typical notion of the atom is based on an idea proposed more than twenty-three centuries ago. In order to understand how our notion of the world might be reduced to invisible things, it is necessary to walk down a tenuous journey taking into account the evolution of human knowledge development and what "science," along with its parts, means. The same goes for understanding light, a controversial subject central to our most basic human trait, present in everyday life without further questioning and wonder.

Kuhn already stated that Planck's atomic quantum theory was a scientific revolution, and the main objective of this essay is to find out if the changes in the concept of light (particle or wave) over the years can also be classified as scientific revolutions.

First, it is utterly necessary to address two interconnected areas of science: history and philosophy. Philosophers of science investigate the logical structure of scientific theories and the historical dynamics of their development, modifications, and even replacement. In a period posterior to World War II, most philosophers of science were logical positivists who believed that science involved two stages, going from empirical research to logical analysis of the results. The study of the history of science is relatively new compared to history itself: it started first in the United States in the 1950s and later spread worldwide. Before the creation of such a career path, practically everything we knew about science development resulted from the research and writings of historians who chose to specialize in science and scientists who saw history as a by-product of pedagogy (Kuhn [1977]).

For many years, the pattern of presenting the history of science to students was done through opening chapters in books, treatises, and monographs, and it was usually optional to teach it. Consequently, many educators must be more interested and willing to engage their pupils in deep, tangled webs. This approach, or absence of it, can shine reasonably if we consider the fact that we do not know what those scientists were thinking when they produced a particular piece of work. As I intend to explain further, neither do the own scientists, who find themselves lost in other's conclusions from previous scientific revolutions.

In history, the finished product of research disguises the nature of the work that produced it (Kuhn [1977]) and even the thoughts and actions of the people behind it. Both the philosophy of science and the history of science came to change because of the works Thomas Kuhn, Karl Popper, Imre Lakatos, and Paul Feyerabend developed in the 1940s and further.

Second, we need to clarify what this means to categorize an event as a scientific revolution. This will be presented and explained later. Regarding atomicity and light, most of what we know is well-defined and has already been well-studied by specialists and those who know better, but it is essential to address some of the historical events in science.

We have come a long way since the start of splitting knowledge into segments. It all began with astronomy, stats, and optics during the Hellenistic period, and such parts of the physical sciences had their vocabularies and techniques (exclusive to practitioners). From the fifth century B.C. onwards, we added mathematics and harmonics to the cluster of classical sciences, the first lingua franca adopted by the group and its defining factor of differentiation.

Not only Greece and the Mediterranean contributed to the cluster's development, as we were taught at an early age, but Islam itself. Pinpointed in history nine centuries later, it grew similarly, especially in optics and algebra. The transitions of geometry to algebra, circular to noncircular orbits in astronomy, the new theory of vision, the first acceptable solution to the problem of refraction, and a completely new theory of colors were some of many other new chapters in the book of classical sciences written over Islamic studies (in contrast to European universities, Islamic universities were majority established and funded not by the state, but privately).

The frequent need for observations and experiments peeked astonishingly in the seventeenth century, as depicted in many treatises that reserve long chapters for the Enlightenment, and gave birth to a new experimental movement named after Francis Bacon: the Baconian inductive method of reasoning. Famous followers of this method were Gilbert, Boyle, and Hooke, great performing experimentalists who rarely aimed to demonstrate what was already known.

Though one can, in principle, deduce the ability of flames to burn flesh, it is more conclusive to place one's hand in the fire, but no one will do it to prove a point. If Baconianism contributed little to new developments in classical sciences, it did give rise, nonetheless, to a large number of new scientific fields. A remarkable specific trait of seventeenth-century scientists such as Galileo, Kepler, Lagrange, Descartes, and Newton was their easiness in changing study areas, going from mathematics to astronomy and statics to optics and the study of motion. According to Kuhn [1977], while

> "(T)he corpuscularism which underlies much seventeenth-century experimentation seldom demanded the performance (...) of any individual experiment, Newton's prism experiment would have been no more effective than its traditional predecessors in transforming the theory of colors if (he) had not had access to the newly discovered law of refraction."

This contrasts with previous nontraditional experiments responsible for revealing effects such as interference, diffraction, and polarization. During the Scientific Revolution, transformations endured by the classical sciences were more related to new ways of looking at old phenomena rather than a series of unanticipated experimental discoveries.

Perhaps except for his contemporaries Huygens and Mariotte, Newton set an incredible double mark, rarely seen in the eighteenth century and ahead. While his Principia lies within the natural sciences tradition, Opticks is unequivocally Baconian (Kuhn [1977]). Optics was not a new field composed of theories and experiments (as documented in Boyle's Experimental History of Colours); Newton, the last magician, was responsible for juxtaposing and improving what was already known but in a broader light. Before him, in the early seventeenth century, many philosophers of science sought to replace Aristotelian concepts, and, as a consequence, a new area of natural science arose: mechanical philosophy.

Based primarily on the works of Gassendi (a mixture of Christianity and Epicurean atomism in the void) and Descartes, the light was corpuscular, which is how Newton portrayed it in his works. Refraction and reflection's geometric nature could only be explained if one assumed light is indeed a corpuscle, going against what Huygens preached. For him, light was a wave, as seen in *Traité de la lumière* when he discuss the intricacies of the phenomena of the double refraction of crystals and the atmosphere's refraction.

Huygens' works on wave theory were still ongoing, but they opened the road to Young's and Fresnel's studies on transverse vibrations and interference. Such conflict regarding the nature of light prepared the stage for two different lines of thought: on one side sat the wave theory, and on the other sat the corpuscular theory.

The fact that Newton was much more famous than Huygens may have had an impact on how scientists favored him for a while. Newton's legacy and favoritism lasted more than one hundred years. Practically all scientists at that time believed in ether (echoing Descartes), something indispensable to Huygens' wave propagation, and witnessed a wide range of experiments showing the wave nature of light. Young's single-slit experiment showed diffraction and interference patterns like those exhibited by energy waves, and after Young's experiment, the bar started to weigh toward Huygens' theory (Buchwald [1989]).

A change of scenario in the nineteenth century resulted from the newly developed Maxwell's theory of electromagnetism. Huygens, along with Rømer, proposed 22000 km/s for the velocity of light, which was a fair estimative due to the technological apparatus at the time. In 1862, Foucault obtained a value of 298,000 km/s, while Fizeau found 315,000 km/s. The value Maxwell calculated was somewhere in between the two. Such a number appeared as a particular constant in Maxwell's equations. This constant was deduced from the coefficient of aberration and the received value of the radius of the earth's orbit, which was a result of applied mathematics to laboratory experiments' values on electricity and magnetism.

Indeed, Maxwell's equations showed wave-like solutions, and he proceeded to calculate its velocity. He was probably surprised when his calculations linked to a number that happened to be close to the speed of light. In his 1864 paper, A Dynamical Theory of the Electromagnetic Field, he concluded that "the agreement of the results seems to show that light and magnetism are affections of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws."

The world did not know what to do with Maxwell's calculations for a while. They were so new that Hertz would come out with radio waves only twenty years after his publication. Technology is hardly hand in hand with the scientific development of an era, partially because, as Kuhn was going to formulate later in the twentieth century, theories take time to settle down, and scientists spend a considerable moment engaging in puzzle-solving before encountering-if so-incongruities. While physicists were dealing well with the wave behavior of light, chemists were busy formulating and improving a better atomic theory for the matter. Lavoisier, Dalton, and Proust kept their minds occupied with new laws such as conservation of mass, proportions, and indivisibility. In the meantime, Mendeleev and Avogadro contributed to the creation of the Periodic Table and completed the basic atomic theory. However, some things were about to change by the end of the nineteenth century.

Thompson discovered the electron in 1897, transforming the way scientists approached electricity: it would no longer be considered a fluid but a ray of ordered particles. This discovery was a problem for classical electrodynamics because the theory was based on the notion of fluidity, so Maxwell's fields (continuous wave-like entities) had to be rethought.

Not only did Maxwell's theory call for a revision, but Planck brought up new studies concerning radiation. After observing the spectrum emitted by a glowing object (hot objects glow, and hotter objects glow brighter than cooler ones), he published Über eine Verbesserung der Wienschen Spektralgleichung in 1900, a paper responsible for changing and shaking the structures at the time. In it, he expatiated about an ad hoc mathematical assumption of the quantized energy of the oscillators that emit radiation (Kragh [1999]), a necessary move since there was no way of matching the equipartition theorem to electromagnetic emission-the famous black body problem. We know that, when in equilibrium with light, a hot object absorbs just as much light as it emits, but if the object is black, then its thermal light emission is maximized since it absorbs all the light that hits it.

Before Planck's work, there was a consensus that a body's energy could take on any value (it was a continuous variable). Instead, Planck concluded that the light's frequency emitted by the black body depended on the emitted oscillator's frequency (a result of his equations of motion for light), and the energy increased linearly with frequency, multiplied by a constant named after him (Planck [1901]).

There are an integer number of oscillators in thermal equilibrium with the electromagnetic field once they cease to exchange quanta. A quantum of light is formed when the oscillators give their entire energy to the electromagnetic field, and a quantum of light is absorbed when the oscillators are excited by the electromagnetic field. Planck's theory is an atomic theory of light and a quantized electromagnetic field theory. While it seemed reasonable, few physicists were happy with it - including Planck himself.

After working alongside Planck in the quantized energy model, Einstein extended the thought to an old problem concerning the emission of electrons off a metal after light shone on it. In the celebrated 1905 work, *Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt*; he discusses how the previous observation that the energy of those ejected electrons depended only on the frequency of the incoming light-not its intensity-could be mathematically explained by Planck's energy quanta.

As seen before, electromagnetic radiation, such as visible light, was considered to behave as a wave. That is why frequency and wavelength are terms used to describe radiation. Intensity is a light's quality to which we attribute the relation of energy transferred in a given time, but this did not work when it came to energy for the photoelectric effect. An increase in the light source's intensity causes more photoelectrons to be emitted with the same kinetic energy instead of the same number of photoelectrons to be emitted with higher kinetic energy. Einstein solved this issue by saying that light itself is quantized.

The energy of light is not transferred continuously like in a classical wave, but only in small packets of energy - in other words, quanta. These quantum of light were later named photons. From this event on, Bohr was able to quantify the atom as an extension to Rutherford's model, and we saw the birth of a completely new area of physics, which still produces loads of subareas and specialties.

We have seen de Broglie associate a wavelength characteristic to all matter. We have seen Heisenberg's uncertainty principle dictate every aspect of doubt concerning the quantum world. We have reached a satisfactory explanation for the wave-particle duality thanks to the works of de Broglie and Bohm - also known as the Bohmian Mechanics - and we realized we can change how the world is just by interacting with it. As we force a wave function to collapse, or as we see the light as a connection between two fields, we can conclude that everything depends on the question we ask and the problem we are trying to solve.

3 The (not so) smoothy flow: a history of revolutions

"Truth emerges more readily from error than from confusion."
– Francis Bacon

Langhe [2013] starts his paper about Kuhn's paradigm by pointing out a clear issue in the philosophy of science: either theories do not match data, or you may indeed have data but are unable to formulate a theory to explain it.

According to him, Kuhn tried to do both: adequately capture the challenges practiced scientists face without losing normative force. Kuhn successfully changed the approach to the philosophy of science by seeing it through a historical lens and reimagining science based on empiricism and reality. Kuhn argued that science is a social construct and must consider the evolutionary process innate to society itself. It is impossible to dissociate the work of a scientist or a scientific community from its historical context, the exchange that occurs within the environment in which the person or group fits. Empirical historicism replaced justification in his works (Kuhn [1970]).

Kuhn's philosophy of science differs from the traditional philosophy of science because he took a step back in time rather than starting to see science's final products (e.g., dynamic phenomena) at the beginning point. To Kuhn, the final products of science are formed through interactions of individual scientists. In contrast, the traditional philosophy of science opens the evolution's journey of knowledge with the products and then proceeds to change them by introducing external factors.

Such a twist allows thematization of systematic phenomena like schools, paradigms, revolutions, and emergents of components' interactions, but they are not reducible to them. Kuhn [1977] later extended the thought to fit the past-future conflict's evaluation: Do we choose a theory based on optimization of the current knowledge, or do we aim it at increasing the amount of future knowledge? According to him, scientific rationality is about choosing the fittest way to practice future science instead of adopting what is currently best (Langhe [2013]), and the manner of doing so consists of being able to look backward at the final products (exploitation) and forward in practicing future science (exploration).

In Kuhn's own words, "Scientific development must be seen as a process driven from behind, not pulled from ahead - as an evolution from, rather than evolution towards" (Kuhn [1970]). Rationalizing the true or false nature of outcomes' current evaluation does not matter because they are simply in place; they are "part of the historical situation within which this evaluation is made" (Kuhn [1970]).

Langhe [2013] argues that Kuhn probably realized his approach to science was an instance of a family of models we nowadays call complex systems. Science emerges from specific interactions of scientists over time, and what makes a system complex instead of merely complicated is that the rules governing the interactions change with time.

Since complex systems do not need to have an endpoint, it solves the critique shared by Weinberg [1998] and several others that characterizes Kuhn's views of scientific progress as undirected improvements but not improvements toward anything - nature's built-in sets did not inevitably point science towards the direction of Maxwell's equations or Einstein's general relativity, for example. Instead, exogenous chance events eventually lead to endogenous changes through a "feedback loop through which theory change affects the values which led to that change" (Kuhn [1977]).

While such a loop allows reinforcement, it makes it possible for scientific revolutions to occur and quasi-homogeneous information-shared communities to arise (Langhe [2013]). These communities self-organize themselves based on commitments to what Kuhn famously attributed to the word "paradigms" (Kuhn [1962]). It is expected that the result of these communities' interactions will be more straightforward and stabler if compared to the interactions within communities themselves, and the way to operationalize paradigms goes beyond the network: it has to describe what science is and explain why it works. Hence, science is progress, not a sum of parts.

Once interactions cease to exist, the product is gone, and the structure is dismantled, no longer understood as a consequence of social and historical attitudes toward the unknown (Langhe [2013]). Kuhn characterizes history as a circle of normal science, crisis, and revolution.

According to Kuhn, in a systematic scientific test, "statements" - or hypotheses - are repeatedly put to proof to serve as a bridge between a scientist's research problem and an accepted scientific knowledge corpus (depending on the area). If the bridge is solid, the scientist has discovered or solved the previously proposed puzzle. If the bridge fails, scientists fix it by implementing new reforms or redirecting it somewhere else.

The bridge's construction is what Kuhn calls "normal science" or "normal research." During this period, there is a tendency among scientists to agree on what phenomena are worth examining, what embodies an explanation of such phenomena, what problems are relevant to solve, and what comes be their solutions. Kuhn's Harvard background in condensed matter, an area of physics known today to deal with complex systems (e.g., magnets, superconductors), might explain why he contextualized the idea of complex systems into a disciplinary matrix. A disciplinary matrix is nothing more than a set of ordered paradigms, or a set of paradigms, tied to a specific community of scientists. Just like a complex system consists of many components - in which one constituent does not necessarily need to interact with another - that can be classified according to one's will or view, the disciplinary matrix presents its elements in three different categories:

- Symbolic generalizations (expressions deployed without question by the group or community);
- Models (what provide the group with preferred analogies - e.g., gas behaves like a collection of microscopic billiard balls);
- Examples (concrete problem solutions, also used to design the second name of "paradigms").

Kuhn further states that to understand a community, one must understand how those three components of the disciplinary matrix operate. If one alters any of the components, it will initiate a change in the scientific behavior, which, as a consequence, will affect both the locus of one's group research and its standards of verification (Kuhn [1970]).

Normal science "is an enterprise which accounts for the overwhelming majority of the work done in basic science (...) when engaged with a normal research problem, the scientist must premise current theory as the roles of his games" (Kuhn [1970]). Both paradigms and disciplinary matrices characterize the period of normal science, and only within the context of a paradigm can we speak of one true or false theory.

Kuhn had a particular appraisal of Darwin's evolution theory, and he usually used Darwin's work as an analogy to his own. For Kuhn, the natural selection of scientific theories is driven by problem-solving. If some problems cannot be solved using existing theories during a normal science period, the natural proliferation of new ideas is expected. As Darwin described in his theory, the surviving ideas are the ones that do best at solving those problems.

Part of what distinguishes a community of scientists is the language they use, a "lexical taxonomy"- or "lexicon" in Kuhn's words-usually, they attribute whole concepts to single words or symbols, mimicking a behavior long possessed by animals and early humans. This specificity acquires an aspect of evolutionary epistemology, being raised in numbers after every revolution, which might come from the intersection between two or more preexisting specialties (e.g., molecular biology).

To Kuhn, inevitable specialization is the price we pay for increasing powerful cognitive tools (Kuhn [1970]). However, it is a problem - just like speciation on evolutionary terms - since it becomes hard to date the time of its occurrence and creates a communication barrier concerning those outside the community.

Conversely, Kuhn also stated that "lexical diversity and the principled limit it imposes on communication may be the isolating mechanism required for the development of knowledge" (Kuhn [1970]), leading us to think it is an inescapable zero-sum game analogously and that incommensurability arises naturally from a paradigms' crush (e.g., overthrow of Ptolemaic cosmology by Copernican heliocentrism - depicted above

- and the displacement of Newtonian mechanics by general relativity and quantum physics).

A shift in the paradigm alters the fundamental concepts underlying research and inspires new evidence standards, research techniques, and alleyways of experiment and theory that are thoroughly incommensurate with the old ones.

Regarding acceptance or rejection of a theory or statement in the face of evidence shared by all, he believed that, firstly, we need to ask if the theory or statement is a candidate for proper/false judgment, meaning it is lexicon-dependent and exclusive. There is no space in the science game for asserting both, and such breakdowns in communication are significant of the episodes Kuhn refers to as "crises" (Kuhn [1970]), with an essential consequence of knowledge growth. In scientific revolutions, not only do scientific theories change, but the very standards by which scientific theories are judged are modified, making the paradigms that govern successive periods of normal science incommensurable.

Lakatos [1977] highlights the bias intrinsic to theory choice by saying, "no degree of commitment to beliefs makes them knowledge (...) blind commitment to a theory is not an intellectual virtue, it is an intellectual crime". Indeed, one can turn to inductive logic, yet, as Popper advocated, "scientific theories are not only equally unprovable but also equally improbable" (Lakatos [1977].

Popper's falsifiability criterion (proposing tests aimed at exploring the limitations of an accepted theory or subjecting the current one to an uttermost struggle) has always been an easy target for his colleagues' criticism, just as Kuhn's notion of scientific revolutions. Meanwhile, their contributions fomented debates and led to a broader range of subareas in philosophy, sociology, and natural sciences. During scientific revolutions, the participants are, in a sense, living in two worlds: the earlier period of normal science, which is now breaking down, and the new period of normal science, which is not yet entirely comprehensible.

Theories gain such new clothes in a paradigm shift that it is practically impossible for scientists after a scientific revolution to see things like they had been seen under the previous paradigm. Today, looking back to Maxwell's 1873 Treatise on Electricity and Magnetism, it is hard for any modern physicist to read because it is based on the idea that electric and magnetic fields represent tensions in the ether (an ancient and outdated notion we no longer believe in). In this respect, there is a pre-Maxwellian aspect to his theory, which should not be a problem for us since we always deal with conflicting theories.

However, how hard is it for us to refrain from condemning new ones? After our current period of normal science, in which the implications of the Standard Model are being calculated by theorists and tested by experimentalists, has come to an end, we soon might witness a crisis regarding the atom, which emergency will provoke a change in the contemporary paradigm. Not that we are closer to the truth since, according to Kuhn, all past beliefs about nature have turned out to be false. However, it does not necessarily imply that we can not enjoy scientific advances and technological developments.

4 A bright move

According to Kuhn, a revolutionary paradigm shift is an inescapable outcome, and as a result, an entire explanatory framework is substituted. Planck agreed that it takes large-scale internal conundrums in a scientific community to cause a shift in how natural laws are discussed, but this does not imply that a new paradigm will be psychologically easy to accept afterward.

All the data can point in a certain direction, yet it takes more than reason for a scientist to start propagating new ideas. The longer a model is established, the more resistance is expected from the group-one does not calmly accept the model's destruction or reinvention. Cognitive values are ultimately a matter of subjective preference that transcends rationality. Kuhn parallels Planck in the statement that scientists find it challenging to overcome novelties (Gernand and Reedy [1986]). Suppose this is necessary to classify an event as a scientific revolution. In that case, the wave-particle duality has undergone a couple of paradigm shifts, especially in the transition of models from Newton to Huygens and from Planck to

Einstein to Bohm.

More than that, the difficulty of understanding light's nature permeated through three centuries and involved key periods of crisis, during which certain scientists used a notion while his colleague wrote extensively using a different approach.

After a crisis comes the revolution, which is characterized, among several other aspects, by the birth of new areas of study, it is likely that before Newton and Huygens' disagreement-one based on their empirical experiments-scientists experienced an extensive period of normal science regarding light's nature, which ceased to exist as long as the disagreement began.

How one could have handled theory choice, incommensurability, and falsifiability at the time is a question for further investigation. Planck's work shifted our way of seeing the world from a classical perspective to a quantum perspective. During science's evolution, new knowledge would replace ignorance rather than replace knowledge of a different sort. If we are closer to the truth now and something like it exists, only time and a deeper analysis of nature can tell.

5 Conclusion

Kuhn, closer to the end of The Structure of Scientific Revolutions (1962), asks, "Is it any wonder that the price of significant scientific advance is a commitment that runs the risk of being wrong?" and I answer no. The search for the truth might be a burden to those who do not possess the grit to endure an unstable voyage, but it is worth it. Physicists, chemists, and all sorts of scientists experienced some uncertainty about their studies and careers, yet they were fruitful. The study of light's dual nature and its revolutionary and contrasting aspects provided incredible technological progress, which we cannot live without anymore. If today, humanity - in general - still does not know what light is, then does it bother?

6 References

Jed Z. Buchwald. *The Rise of the Wave Theory of Light*. The University of Chicago Press, Chicago, IL, 1989.

H. Gernand and W. Reedy. Planck, kuhn, and scientific revolutions. *Journal of the History of Ideas*, 47(3):469–485, 1986.

Helge Kragh. *Quantum Generations: A History of Physics in the Twentieth Century*. Princeton University Press, Princeton, NJ, 1999.

Thomas Kuhn. *The Structure of Scientific Revolutions*. The University of Chicago Press, Chicago, IL, 1962.

Thomas Kuhn. *The Road Since Structure*. The University of Chicago Press, Chicago, IL, 1970.

Thomas Kuhn. *The Essential Tension*. The University of Chicago Press, Chicago, IL, 1977.

Imre Lakatos. Science and pseudoscience. In Imre Lakatos, editor, *Philosophical Papers*. Cambridge University Press, Cambridge, 1977.

Reinout De Langhe. The kuhnian paradigm. *Topoi*, 32(1):65–73, 2013.

Max Planck. Ueber das gesetz der energieverteilung im normalspectrum. *Annalen der Physik*, 309(3): 553–563, 1901. English translation: On the law of distribution of energy in the normal spectrum.

Steven Weinberg. The revolution that didn't happen (thomas kuhn's view of scientific progress). *New York Review of Books*, 45(15):48–52, 1998.