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The Nature of Normal Science: Arthur Compton's Research Programme as an Exemplar

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Thomas S. Kuhn's theory of normal science (NS), aside from being a provocative philosophical reconstruction of the relatively conservative phase of scientific research, contains useful ideas for systematic analysis of specific episodes in the history of science. Therefore, although the theory has been looked at from different angles since the first edition of *The Structure of Scientific Revolutions* (TSSR) was published in 1962, its detailed exploration of the cumulative phase of research in mature science is of abiding relevance in the philosophy of science. This is because NS provides a compelling account of how and why members of scientific communities succeed, largely, to produce reliable knowledge about an incompletely known phenomenal world. Again, the theory elucidates special features of scientific research that differentiate it from other creative enterprises. In that regard, this paper reconstructs Arthur Compton's research into x-ray scattering as a good instantiation of NS. Discussion of Compton's convincing demonstration of the particulate properties of electromagnetic radiation within the framework of NS showcases the elucidatory power of Kuhn's theory with respect to selected episodes in science, and corroborates the notion that the bulk of scientific work is a conservative puzzle-solving activity with the potential for precipitating scientific revolutions. To the best of my knowledge, this is the first time that Compton's groundbreaking work on x-ray scattering has been analysed within the framework of Kuhn's philosophy of science.

Keywords: normal science, paradigm, disciplinary matrix, scientific community, x-ray scattering, Compton Effect

1. Background Analysis

The theory of scientific knowledge and its growth formulated by Thomas S. Kuhn in *The Structure of Scientific Revolutions* (*TSSR*) represents a decisive statement of what is sometimes called the "historical turn" in the philosophy of science (Rosenberg 2005, 145-155; Bird 2010, 66-77; Carrier 2012, 132-151). According to Dudley Shapere, the fundamental theses of the book constitute a revolution, or at least a rebellion, in philosophical critiques of scientific knowledge (Shapere 1992, 28). The rebellion involves not only criticism of the main traditions in the philosophy of science, but also constitutes a provocative re-examination of orthodox theories about scientific knowledge, its evolution, structure, and justification, together with interesting ideas about what the legitimate problems of the philosophy of science should be and the appropriate method for tackling them. Nancy Nersessian describes the research project outlined by Kuhn as intrinsically historical, philosophical, and psychological (Nercessian 2003, 178. See also Fuller, 2000).

Before publication of the first edition of *TSSR* in 1962, logical positivism and falsificationism (or critical

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rationalism) dominated the philosophy of science. Briefly stated, leading members of the two schools of thought, despite profound differences in their approaches with respect to the demarcation problem, the status of metaphysics and foundational principles in science, the structure of scientific explanation and truth shared similar logistic concerns about philosophical reconstruction of scientific knowledge (Carnap 1936/1937; Ayer 1959; Popper 1959; Richardson & Uebel 2007). For Rudolph Carnap, Hans Reichenbach, and Karl Popper particularly, socio-psychological factors associated with serious scientific research properly belong to the "context of discovery" and not to the "context of justification" wherein theories are severely tested and appraised in accordance with well-defined objective standards. As a corollary, the acceptance or rejection of scientific theories depends solely on objective criteria of logic and evidence, such that as science continues to progress biases and other "external factors" inimical to scientific objectivity will become increasingly irrelevant because of improvements in standard mechanisms of theory evaluation and error elimination.

Now, even before the "historical turn" emerged in the philosophy of science around the 1950s, cracks were noticeable already in logic-dominated theories of science. To begin with, logistic theories rarely contain rigorous philosophical accounts of the extended creative processes involved in discovery and conceptual change in science. Instead, they overemphasize the standard objective criteria or logical rules for the "game of empirical science" which, according to Kuhn, put science in a Procrustean bed. Generally, logical positivists and falsificationists believe that the actual processes of discovery are too intuitive and mysterious to permit systematic philosophical elaboration, on the supposition that there is a fundamental epistemological hiatus between "the context of discovery" and the "context of justification." Kuhn, Howard Margolis, Nancy Nercessian and others, however, argue convincingly that any sharp distinction between the context of discovery and the context of justification must be arbitrary because in practice discovery and justification interpenetrate each other (Kuhn 1977, 320-339; Margolis 1987; Nercessian 1992, 3-45). Moreover, both are philosophically analysable in terms of human representational and problem-solving capabilities actualized within social contexts. Studies of the research practices of scientists provide concrete and empirically justifiable insights into the dynamic processes through which a "bold conjecture" (to borrow one of Popper's characteristic locutions) is formulated into a genuine scientific theory, gets communicated to other scientists, and eventually replaces previously accepted representations in a scientific field. One of such insights is the impossibility, in principle, of formulating non-defeasible epistemological criteria for differentiating sharply between discovery and justification within the social ambience necessary for the production of scientific knowledge.

Secondly, realists' claims connecting purported "best" or "most verisimilar" scientific theories and empirical evidence have the character of a red herring since, according to an argument whose origin is traceable to Pierre Duhem and W.V.O. Quine, scientific theories in general are underdetermined by empirical evidence (Duhem 1906; Quine 1969; Newton-Smith 1979, 72; Laudan & Leplin 1991, 449-472; Kosso 1992; Earman 1993, 19-38; Hoefer & Rosenberg 1994; Kukla 1998). Anti-realists (sometimes called relativists) argue that there will always be more than one theory consistent with any collection of relevant data—even if the data were to include all empirical data (Blackburn 2005, 375). If the thesis of underdetermination is correct, then there is no guarantee that all possible data appropriately interpreted will yield a particular theory as the unique "correct" choice. However, some philosophers of science, notably Charles S. Pierce, maintain that, in principle, improvement in the experimental methods of science will converge on the true theory (Peirce 1992, 139). In Popper's watered down version of realism, the severest tests corroborate the best theory, on the ground that corroborability, or degrees of corroboration, are a function of the severity of tests (Popper 1959, chap. X).

The complex issues associated with underdetermination and the extent to which scientific theories are undetermined by data have not been completely settled (Psillos 1999; Ladyman 2001; Douven 2010; Seager 2012, 213-232). Nonetheless, an important outcome of current discussion on the subject is increasing realization by philosophers of science that making well-informed judgment about the status of a theory in relation to a given body of evidence is more problematic than what was previously thought. For instance, one of the strongest arguments for scientific realism is the claim that well-established scientific theories are successful because their observational predictions tend to come out true. Yet, practical demonstration of "reasonable agreement" between theoretical predictions and experimental findings is a challenging task, which requires painstaking work and skill and seldom leads to definitive conclusion (Kuhn 1977, 178-224). Thus, from a more experiment-oriented perspective, the success of scientific theories depends on complex heuristic modelling processes and mathematical calculations that define what the relevant data are, in the first instance, followed by rigorous piecemeal researches that determine how and to what extent available data connect to available theories before scientists can reach a consensus on the theory with the least amount of probable error (Mayo 1996).

Unlike the positivists and falsificationists, Kuhn formulates his theory of normal and extraordinary science as a descriptive cum prescriptive account of the cumulative and non-cumulative stages of scientific research. His model of scientific development depicts succession of its major phases according to the following schema: pre-paradigm science → normal science → anomaly → crisis → extraordinary (revolutionary) science → new normal science, etc.

The image of science depicted above illustrates the rapprochement between the history of science and post-positivist philosophy of science. Now, Kuhn does not set out to demolish the "received view," the latter being a blending of deeply entrenched ideas inherited from traditional rationalism and empiricism epitomised in the writings of René Descartes and David Hume. He accepts that science is a rational activity that generates reliable knowledge of the objective world. Nevertheless, he characterizes that very rationality differently by paving the way for a more open, flexible, and historically oriented understanding of science (Bernstein 1983). The concept of normal science (NS) is integral to Kuhn's idea of what science is like and ought to be like. Arthur Compton's research programme, which culminates in his discovery of the Compton Effect, is a good example of NS. As a necessary first step towards substantiating the claim above, we present a brief outline or silhouette of NS.

2. An Outline of Normal Science (NS)

Before the emergence of NS, Kuhn says, the investigation of any aspect of nature was carried out by competing schools and sub-schools that espoused one variant or another of existing explanations of phenomena in that domain (Kuhn 1970b, 12). Because there was no consensus by researchers on fundamentals, such as foundational methodological principles, exemplary problems, and problem-solutions, each investigator was compelled to build his field anew almost from scratch. Consequently, even though the men and women who studied nature during the pre-paradigm stage in the evolution of a scientific specialty were scientists, the net resulting of their activity was something less than science since, as already indicated, a common body of beliefs each investigator could take for granted in his or her studies was lacking. According to Kuhn, "history suggests that the road to a firm research consensus is extraordinarily arduous" (Kuhn 1970b, 15). The pre-paradigm stage usually ends and NS commences when one of the competing schools triumphs over its rivals, mainly because its own characteristic beliefs and basic assumptions emphasize only some special part of the considerable and inchoate pool of information that eventually proves particularly revealing of the nature of phenomena studied by the rival groups. Of course, NS does not begin at a clearly defined instant in time: As Kuhn explains, emergence of the sort of research characteristic of mature science is the culmination of an extended complicated process, which takes time and considerable effort from different researchers (Kuhn 1970b, 16-22).

Kuhn defines NS as research firmly based upon one or more past scientific achievements that some particular scientific community acknowledges for a time as supplying the foundation for its further practice (Kuhn 1970b, 10). Such achievements must be unprecedented to the extent of attracting an enduring collection of practitioners away from rival modes of scientific research, and open-ended enough to leave all sorts of research problems for the redefined group of researchers to resolve. NS is a rigid, paradigm-guided, puzzle-solving activity. The paradigm concept plays a pivotal role in NS, but Kuhn's initial definition of it as a universally recognized scientific achievement, a classic scientific textbook, a set of shared values, an exemplar, gestalt figure, a global scientific tradition etc., creates confusion with respect to what, fundamentally, a paradigm represents (Kuhn 1970b, 23-25; Masterman 1970, 59-90; Hoyningen-Huene 1993, 131-162; Bird 2010, 69). As a result, Kuhn introduces "disciplinary matrix" to reduce the confusion by focusing on the cognitive core of "paradigm." A disciplinary matrix (DM) is the common possession of experts in a scientific discipline; it comprises ordered elements of a certain type, each requiring further articulation and specification (Kuhn 1977, 293). Three components of DM are central to the research activities of members of a scientific community. The first is symbolic generalizations, that is, concepts routinely employed by scientists and expressible in some logical or mathematical form. The second element comprises models which provide the group with preferred analogies or, when deeply entrenched in the epistemic repertoire of scientists, with an ontology. Finally, there are exemplars, that is, concrete problem-solutions accepted within a given scientific community as paradigmatic and used directly as a concrete model of competent practice (Kuhn 1977, 297-308; Hoyningen-Huene 145-158; Bird 2010, 69).

In every research tradition defined by consensus on a DM, Kuhn identifies three major interconnected foci for both factual and theoretical investigations in NS, the major purpose of which is to make accepted paradigm more determinate and precise in the course of applying it to selected phenomena in that particular domain of research. They include determination of the value of constants in equations, perfecting experimental techniques and extending the application of accepted theory to new domains of application (Kuhn 1970b, 25-34; Bird 2010, 68). Kuhn likens the research problems of NS to puzzles in order to highlight their peculiar blend of mathematical and empirical features, together with the kind of mindset it engenders in practitioners, which differentiate them from the type of problems that constitute the subject matter of other creative disciplines (ibid., 35-42).

Scientists working within a tradition of NS share a great deal in terms of methodology, accepted theory, instruments, experimental techniques, and exemplars. The bulk of their job, *qua* scientists, is "a complex and consuming mopping-up operation that consolidates the ground made available by the most recent theoretical breakthrough and that provides essential preparation for the breakthrough to follow" (Kuhn 1977, 188). Scientists engaged in the mopping-up operation are participants in a tradition of research, which is the characteristic activity of the subculture responsible for sustaining the tradition (Barnes 1994, 89). According to

Kuhn, steady extension of the scope and precision of scientific knowledge characteristic of NS is impossible without commitment to accepted theories (DM).

Kuhn is unique among philosophers of science for stressing the pedagogic effectiveness of science textbooks and laboratory work in producing the mindset necessary for scientific research. Training for the practice of NS is rigid and authoritative precisely in order to inculcate the highest possible commitment to an accepted paradigm and the least possible inclination to conduct research outside it. Consequently, the relative immunity of paradigms to Popperian falsification during NS provides a basis for single-minded pursuit of paradigm articulation, which is a necessary precondition for overcoming enduring challenges. Thus, in striking opposition to Popper, Kuhn insists that it is characteristic of mature science that members of a scientific community do not discuss critically the fundamentals of their discipline (Kuhn 1970a, 241-249 & 1970b, 77-81; Bird 2005; Fuller 2012, 36-37). In other words, normal scientific research rarely involves severe tests aimed at falsification of theories, which Popper sees as the linchpin of scientific progress. Kuhn repeatedly argues that commitment to an existing paradigm theory is a prerequisite for scientific progress because it allows for the tenacious pursuit of paradigm articulation prerequisite for detecting significant anomalies that trigger scientific revolutions.

In spite of the rigidity and conservatism of NS, however, it possesses an in-built mechanism that ensures relaxation of the constraints that bound research whenever the paradigm from which they derive no longer functions effectively. Moreover, because of human fallibility and complexity of the phenomenal world, paradigms are born with anomalies. In most cases, these anomalies are resolved through further articulation of accepted paradigm in the course of normal research or shelved for the moment as research problems for the future. Kuhn emphasizes “significant” or “fundamental” anomalies, that is, anomalies that “penetrate existing knowledge to the core” (Kuhn 1970b, 52-65). Such anomalies emerge “in an area that is particularly significant for the underlying theory or its application (or which is central to the employment of some important technique or piece of apparatus) and continue to defy solution” (Bird 2010, 68).

Kuhn presents a fascinating account of how significant anomalies of this kind open the door to radical or revolutionary changes in science, as usual relying heavily on his mastery of relevant historical episodes. Generally, when scientists detect a significant anomaly (or anomalies), the current paradigm is not discarded immediately—that, as Kuhn claims, would be tantamount to the abandonment of science altogether. Instead, scientists in the field currently experiencing crisis become more speculative and wide-ranging in their research, more accommodating of novel “bold conjectures.” The very experienced scientists, due to entrenchment, tend to stick with the ailing paradigm hoping that it would resolve the anomaly eventually. Other scientists who, usually, are younger or less experienced in the discipline, will likely explore the possibility of an alternative paradigm, a new scientific achievement that can both assimilate the currently problematic body of accumulated anomalies and serve, like its predecessor, as a concrete model for future work. However, before the new paradigm is finally accepted, it must preserve most of the established problem-solutions of the one it replaces. This is how Kuhn describes symptoms of the transition from normal to revolutionary research:

> The proliferation of competing articulations, the willingness to try anything, the expression of explicit discontent, the recourse to philosophy and to debate over fundamentals, all these are symptoms of a transition from normal to extraordinary research. It is upon their existence more than upon that of revolutions that the notion of normal science depends. (Kuhn 1970b, 91)

The transition period ends when: (1) consensus on a new paradigm emerges after elaborate discussion guided by an admixture of idiosyncratic factors and the standard values shared by members of the scientific community; (2) group commitments are re-aligned; and (3) a different tradition of NS is reconstituted around a new paradigm and the old paradigm is relegated.

On the surface, Kuhn's controversial analysis of how and why a new tradition of NS replaces an existing tradition might seem wrongheaded, because it stresses the non-cumulative, a-rational, character of scientific revolutions and highlights the socio-psychological elements at play when scientists have to select the most appropriate theory among competing theories in their research field. Largely, he is correct to underscore the fact that in theory choice, the application of logic and evidence alone (which is problematic, anyway) cannot determine a unique choice for all practitioners of the discipline, since the decision to abandon a paradigm or theory for another entails dialectical interplay of objective and subjective factors. A fair reading of Kuhn's writings shows that his intention is never to claim that scientific inquiry is irrational but rather to show the way to a more open, flexible, and historically oriented understanding of scientific inquiry as a rational activity. He is suggesting that we need to transform both our understanding of scientific inquiry and our concept of rationality (Bernstein, 23).

3. Responses to the Theory of NS

Since Kuhn posited his theory of scientific knowledge over half a century ago, different philosophers of science had taken different positions towards it, especially the theory of NS. For example, Margaret Masterman completely accepts Kuhn's description of NS, despite her complaints about the multiple meanings of "paradigm" (Masterman 1970, 60). As already noted, Kuhn has narrowed the nebulous paradigm concept to its core cognitive components. Popper deplores the conservatism and dogmatism of NS, and believes strongly that the attitude of tenacity to paradigms is dangerous to science (Popper 1970, 51-58). Intermediate positions identify aspects of scientific research adequately explained by NS but criticize the ambiguities and exaggerations in some of the fundamental claims Kuhn made about it, especially the single paradigm monopoly thesis (Lakatos & Musgrave eds., 1970; Bernstein, 20-22; Margolis 1987, 126-127; Bird 2000; Nickles ed., 2003).

Kuhn's argument that deep commitment to paradigms (or theories) is a precondition for rigorous and productive research in science is essentially correct. His recommendation that a scientist should consider working with an alternative to accepted paradigm only when the latter is malfunctioning to an unprecedented degree should be interpreted as a heuristic advice whose violation does not contradict any methodological principle. Nevertheless, contrary to the exaggerated monopoly Kuhn sometimes ascribes to existing theory, researchers competently and legitimately work (and should work) with two or more paradigms to deal with different research problems during NS. As an illustration, in the course of their education, contemporary physicists learn both Newtonian physics and Einsteinian physics. Hence, they can work successfully within the conceptual framework of each theory in the course of research, and once fluency in using the two theories is achieved, they may switch nimbly from one to the other depending on the research problem at hand. This is an important feature of scientific thought process not highlighted, let alone explored, by Kuhn—how a scientist gets from knowing theory *A* to an altered cognitive state of knowing both *A* and another theory *B*, such that she is able to use both for research just as her colleagues who know how to actually use them (Margolis 1987). Thus, scientists can (and do) carry out research successfully within the conceptual frameworks of different theories. Oftentimes, they apply a particular theory to a specific problem, and use a different but more suitable alternative to resolve a different set of puzzles during NS. But none of them can specify precisely how he or she switches from the first theory to the second. Howard Margolis and D. Hull suggest that whatever connections there might be, they are subliminal, reflecting strong and very prolonged Darwinian selection for more efficient, reliable, automatic ways to locate, choose, and sequence both entrenched patterns and relatively recent patterns yet to be fixed in the cognitive repertoire (Margolis, 125-126; Hull 1973).

In summary, Kuhn's theory of NS is a serviceable explanatory framework for understanding paradigm-based normal research, which makes possible the incremental and cumulative growth of scientific knowledge. Therefore, even if, as Kuhn recognizes, his formulation of the concept "created gratuitous difficulties and misunderstandings," NS provides a robust philosophical template for systematic reconstruction of selected (largely non-revolutionary) episodes in the history of science. Arthur Compton's research on x-ray scattering is a classic piece of NS. The next sub-sections shall be devoted to a Kuhnian interpretation of the researches that culminated in the discovery of the Compton Effect.

4. Arthur Holly Compton's Research Programme: The First Phase

To understand the significance of Compton's work on particle scattering, it is necessary to look briefly at the historical background, problem-situation, and state of knowledge concerning the nature of light and electromagnetic radiation generally by the time Compton began investigating *x*-ray scattering in 1917. The nature of light has been a subject of intensive study by researchers since antiquity. Isaac Newton's *Opticks* (1704) gave impetus to the scientific study of the phenomenon by providing detailed elaboration of the corpuscular theory, which explained light as a beam of particles that set up disturbances in "luminiferous" aether, the medium that was believed by scientists to pervade all space. Majority of physicists after Newton accepted the theory and neglected the wave-like features of interference phenomena until Thomas Young established that a wave theory was required for their explanation (Mason 1962, 468-471). Later on, James Clerk Maxwell developed a mathematical theory of electromagnetic field, which depicted light as an electromagnetic phenomenon in the same sense as electricity and magnetism (Maxwell 1873 & 1954). Maxwell's theory explained the propagation of electromagnetic waves through the aether and elucidated Michael Faraday's experimental results on electricity and magnetism. More generally, Maxwell's work became a paradigm for subsequent researches on electromagnetism carried out by Heinrich Hertz, Wilhelm Roentgen, Albert Einstein, and Thomson among others (Cohen 1985; Shamos 1987).

When Compton launched the first phase of his research in 1917, the paradigm for particle scattering investigation was Thomson's classical theory of electrodynamics (Stuewer 1975 & 1976). From the outset, Compton was a conservative scientist deeply committed to classical electrodynamics despite the discrepancy between its predictions and numbers derived from experiments. Like most of his colleagues at Princeton University, he worked within the research tradition headed by O.W. Richardson. In one of such researches, calculations derived from Thomson's theory of *x*-ray scattering indicated that if 0.145 Å *x*-rays pass through aluminum, the rays have a mass absorption coefficient (μ/ρ) of 0.153cm^{2}gm^{-1}. Usually, (μ/ρ) is expressed as the sum of two terms, namely, the mass fluorescent coefficient τ/ρ and the mass scattering coefficient σ/ρ (the latter being, presumably, equal to the Thomson mass scattering coefficient σ_o/ρ). Assuming that the atomic number of an element is numerically equal to half its atomic weight, it can be shown that σ_o/ρ is equal to a constant, 188cm^{2}gm^{-1}. Now, if μ/ρ is equal to τ/ρ plus σ/ρ, and σ/ρ is 0.188cm^{2}gm^{-1}, then the total mass absorption coefficient is smaller than the observed value of one of its components (Stuewer 1976, 618-619).

Compton began the first phase of his research determined to resolve the aforementioned anomaly. He was familiar with the researches of C.G. Barkla and Thomson's classical theory of scattering (Beiser 1995, 72-75; Lal & Ahmad 1997, 29-34). Classical electrodynamics is built on four basic assumptions: (1) Thomson's theory of electrodynamics is correct; (2) the incident electron in a scattering experiment is a point-charge; (3) the electron moves freely within the system; and (4) each incident electron scatters independently (Stuewer 1976, 619). In order to accommodate diffraction, Compton modified assumption (2): He assumed that the scattering electron, rather than being a point-charge, is a large electron with a diameter corresponding to the wavelength of the incident radiation. To make quantitative predictions, Compton had to specify exactly the shape and rigidity of the large electron he postulated, since electrons of different shapes and rigidities scatter and diffract the incident radiation differently. Thus Compton, still under the strong influence of classical electrodynamics, tried several models one after another to determine precisely the size and geometrical shape of the scattered electron.

First, as already noted, he assumed that the diameter of the electron should correspond to the wavelength of the incident radiation. However, experimental data indicated that Compton's electron was too large—almost the entire volume of the atom. In spite of this, Compton proposed that the electron was a large rigid shell of electricity. His calculations suggested that the value for the mass scattering coefficient, σ/ρ, was higher than the value derived from Thomson's point-charge hypothesis and dropped as the wavelength of the incident radiation went down. Subsequent experiments confirmed this. Yet the theory failed to explain the fact that scattered x-rays are a vector quantity, that is, that the secondary radiation travels mainly in a forward direction. To resolve the puzzle, Compton assumed that the electron was a flexible shell of electricity. The large flexible shell model actually predicted a forward-backward asymmetry in *x*-ray radiation; it also predicted the same general behavior of the mass scattering coefficient as did the large rigid shell model.

Keep in mind that Compton's shift from the rigid to the flexible model was methodologically sound: His move was implicit in the steps needed for solving the technical puzzles generated by the first model itself as an explanatory devise derived from the classical paradigm. The flexible model predicted that the soft (or more readily absorbed and, therefore, less penetrating) components of an incident inhomogeneous radiation should be scattered backward to a greater degree than the hard components. This selective scattering effect explained beautifully the earlier observation of D.C.H. Florance in 1910 that the backward-scattered radiation was softer, overall, than the forward-scattered radiation (Florance 1914, 225). Yet the flexible shell model could not predict the correct mass of the electron. Compton tried to invent a model that can do so by replacing the large flexible shell model with another which pictured the electron as a large flexible ring of electricity. This new model was qualitative, but shortly afterwards Compton was able to work out the scattering problem in detail quantitatively. The ring electron model accounted for the observed phenomena explained by the previous two models. Moreover, it explained the mass of the electron and results of some absorption experiments carried out by A. H. Forman (Stuewer 1976, 622).

In October 1919, Compton left Westinghouse for Cavendish laboratory, England, as a National Research Fellow. He performed some gamma-ray scattering experiments at Cavendish, the results of which made him skeptical about the validity of his large flexible ring model, an indication that Compton was not entirely satisfied with the solutions provided by that very model to the mathematically challenging problems he had been working on. Still he did not completely abandon his large electron hypothesis: In fact, he invented a fourth model that represented the electron as a large sphere of electricity. The new model accounted for the observed phenomena previous models explained. Additionally, it predicted an angular distribution for the scattered radiation in the short wavelength region concordant with the new gamma-ray scattering data he got at Cavendish.

5. Arthur Compton's Research Programme: The Second Phase

Shortly after arriving at Cavendish, Compton gradually abandoned his entire large electron research programme, and concentrated on fluorescent research, because he realized that no large electron of a definite radius could explain all the experimental results available at the time (Stuewer 1976, 623-627). Note that the central assumptions of classical electrodynamics, the backbone of Compton's large electron research programme, remained relatively unchanged throughout all the adjustments he made on the large electron model, a situation consonant with Kuhn's theory that the fundamentals of a paradigm are seldom exposed to radical modification or falsification during NS. Thus, Compton continued to work within the classical paradigm even after he had effectively abandoned the large electron programme. In the October 1922 edition of *Bulletin of Natural Research Council*, he reported that "… recent experiments have shown that the size of the electron which must thus be assumed increases with the wavelength of the x-rays employed, and the conception of an electron whose size varies with the wavelength of the incident rays is difficult to defend" (Compton 1922, 10).

At Cavendish Compton reappraised experiments performed earlier by Florance and J. A. Gray (Florance 1914, 225; Gray 1913, 611; 1920, 643), who had concluded that the softening of the incident rays during scattering was a resultant effect of the scattering process. He agreed with them that when gamma rays are scattered, they become softer or less penetrating. Again, he found out that the softest components in the secondary radiation were softer than the softest components in the primary radiation. These results conflicted with Thomson's classical theory, which held that the scattering would be isotropic; that is, distributed uniformly about in the direction of the incident beam. According to Compton, "Thomson's classical theory of the scattering of x-rays, though supported by the early experiments of Barkla and others, has been found incapable of explaining many of the more recent experiments" (Compton 1923). The discrepancy between Thomson's theory and experimental findings convinced Compton to search for a different explanation of electromagnetic radiation.

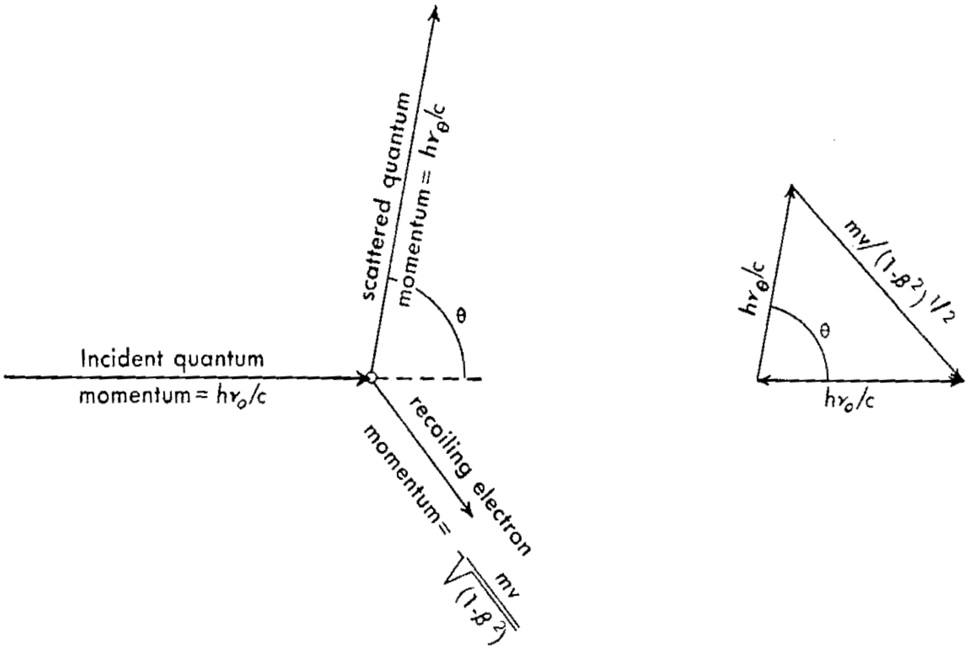
Compton distinguished between "truly scattered radiation" and "fluorescent radiation," that is, between secondary radiation of the same hardness as the primary radiation and radiation softer than the primary radiation. Specifically, he studied experiments on *x*-ray scattering by S. J. Pimpton using homogenous x-rays. Gray had argued that a primary beam of *x*-rays changes into a softer secondary beam if and only if the x-rays consist of electromagnetic pulses, whereas long homogenous waves could never yield softer secondary radiation. Pimpton, after studying Gray's results, reported that he did not find any softer secondary radiation in his experiments. Compton's attempt to resolve these technical puzzles shaped the general direction of the second phase of his research programme (Compton 1921a, 749; 1921b, 96).

The keynotes of the second phase can be summarized as follows (Compton 1922, 18; Steuwer 1976, 628-632; Shamos 351-358). For starters, Compton rearranged his experimental setup. He began to use his crystal or Bragg spectrometer as a wavelength selector, that is, as a device for comparing the spectra of different radiations, instead of using it to generate a beam of homogeneous *x*-rays, as he had done earlier. By 1921, Compton got his first spectra, which demonstrated that when *x*-rays collided with an electron, they bounced off with reduced energy in another direction, a process that resembled the collision of two billiard balls. In the experiment Compton showered a beam of *x*-rays of known wavelength on a block of graphite (carbon or any other material of low atomic weight could serve as well) and the wavelengths of the *x*-rays scattered in different directions at various angles, Φ, were measured with the help of a spectrograph. A comparative analysis of these wavelengths with the wavelengths of the incident beam revealed that while some of the scattered *x*-rays were of the same wavelength as the incident or primary rays, others had a greater wavelength than the incident rays. The scattered *x*-rays that have the same wavelength as the primary *x*-rays (or unmodified *x*-rays) are scattered coherently, whereas rays with greater wavelength than the incident rays (or modified *x*-rays) are scattered incoherently (Compton scattering).

To simplify his calculations, Compton deliberately concentrated on a single electron. He proposed that the electron responsible for the scattering was a free particle at rest before the collision, although it belonged originally to an atom. The free electron assumption was easy to understand within the context of classical electrodynamics, which postulated that some electrons were more loosely bound to atoms than other electrons. At this later stage, and still committed to classical electromagnetic theory as paradigm, Compton struggled to explain adequately the ultimate nature of *x*-rays: He had to decide whether they were electromagnetic waves or light quanta. Einstein's 1905 paper entitled "On a Heuristic Viewpoint Concerning the Production and Transformation of Light" made a strong case for quantum interpretation of electromagnetic radiation. Interestingly, there was no evidence that Compton read Einstein's paper by then, although the idea of light quanta was "in the air" among the physics community, but some physicists vehemently rejected it because the quantum hypothesis contradicted the entrenched wave theory of light (Cohen 423-427).

As far as Compton was concerned, classical electrodynamics was malfunctioning: He had to either resolve the anomaly within the classical paradigm or try a different approach. To move his research forward, Compton introduced the quantum hypothesis into his theoretical calculations—again a response accurately captured by Kuhn's description of how scientists respond (and should respond) when a significant anomaly rears up in normal research. In other words, Compton decided to see what would happen if a single x-ray quantum interacted with a single electron in the scatterer (Fig. 1A below). The idea that during x-ray scattering a single *x*-ray quantum interacted with a single free electron motivated Compton to set up appropriate equations expressing both conservation of energy and conservation of momentum. He solved the equations and derived the value for the change in wavelength of the incident *x*-ray when scattered by a free electron, which agreed with experimental results. Compton's reasoning, as set out in his classic 1923 papers "A Quantum Theory of the Scattering of *X*-Rays by Light Elements" and "The Spectrum of Scattered *X*-Rays," is highlighted below (Shamos, 352-354).

Consider, as in Fig. 1A, that an *x*-ray quantum of frequency v_0 is scattered by an electron of mass *m*. The momentum of the incident ray will be hv_oc, where *c* is the velocity of light and *h* is Planck's constant, whereas that of the scattered ray is hv[illegible]$/c$ at an angle [illegible] with the initial momentum. The principle of conservation of momentum requires that the momentum of recoil of the scattering electron shall be equal to the vector difference between the momenta of these two rays, as depicted in Fig. 1B.



(a) (b)

Fig 1. A and Fig. 1B Source: M. H. Shamos, *Great Experiments in Physics*, p. 252.

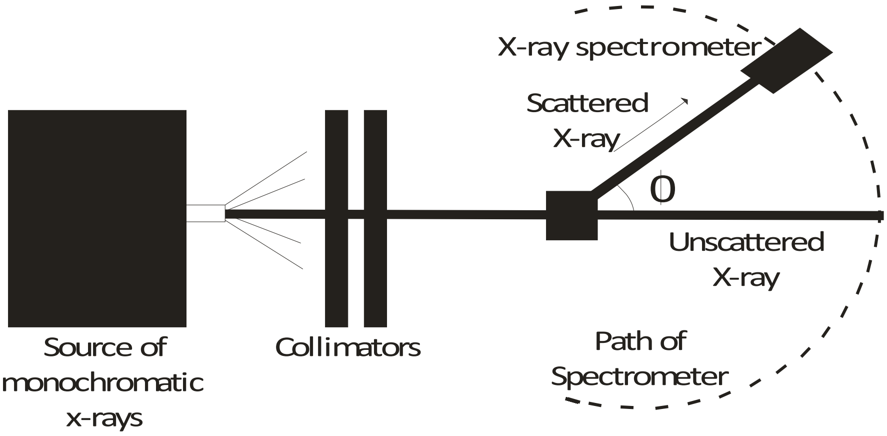


Fig 2. Illustration of the experiment that led to the discovery of the Compton Effect.
Adapted from A. Beiser, *Concepts of Modern Physics* (5th Ed.), p.76.

Consequently, the momentum of the electron, $m\beta c/\sqrt{1-\beta^2}$, is determined by the relation

$$\left(\frac{m\beta c}{\sqrt{1-\beta^2}}\right)^2=\left(\frac{hv_o}{c}\right)^2+\left(\frac{hv_\theta}{c}\right)^2+\frac{2hv_o}{c}.\frac{hv_\theta}{c}\cos\theta \qquad (1)$$

where β is the ratio of the recoiling electron to the velocity of light. However, the amount of energy determined by the formula hv_θ in the scattered quantum is equal to that of the incident quantum hv_0 minus the kinetic energy of recoil of the scattering electron, which implies that:

$$hv_\theta=hv_o-mc^2\left(\frac{1}{\sqrt{1-\beta^2}}-1\right) \qquad (2)$$

Thus, there are two independent equations containing the two unknown quantities β and ν_θ. Solving the equations yields

$$\nu_\theta = \nu_0 \Big/ \left(1 + 2a\sin^2\frac{1}{2}\theta\right) \tag{3}$$

where

$$a = h\nu_0 / mc^2 = h / mc\lambda_0 \tag{4}$$

Or in terms of wavelength instead of frequency,

$$\lambda_\theta = \lambda_0 + (2h/mc)\sin^2\frac{1}{2}\theta \tag{5}$$

It follows from Eq. (2) that $1/(1-\beta^2) = \left\{1 + a\left[1 - (\nu_\theta/\nu_0)\right]\right\}^2$, or solving explicitly for β

$$\beta = 2a\sin\frac{1}{2}\theta \frac{\sqrt{1 + (2a + a^2)\sin^2\frac{1}{2}\theta}}{1 + 2(a + a^2)\sin^2\frac{1}{2}\theta} \tag{6}$$

Eq. (5) indicates an increase in wavelength due to the scattering process that varies from a few percent in the case of ordinary *x*-rays to more than 200% in the case of *Y*-rays scattered backward. Simultaneously, the velocity of recoil of the scattering electron, as calculated from Eq. (6), changes from zero when the ray is scattered directly forward to about 80% of the speed of light when a *Y*-ray is scattered at a large angle. Interestingly, classical electrodynamics entails that if *x*-rays are scattered by an electron moving in the direction of propagation at a velocity $\beta' c$ the frequency of the ray scattered at an angle θ is given by the Doppler principle as

$$\nu_\theta = \nu_0 \Big/ \left(1 + \frac{2\beta'}{1-\beta'}\sin^2\frac{1}{2}\theta\right) \tag{7}$$

Eq. (7) is precisely of the same form as Eq. (3), derived from the hypothesis of the recoil of the scattering electron. Supposing that $\alpha = \beta'/(1 - \beta')$ or $\beta = \alpha/(1 + \alpha)$, the two expressions (3 and 7) become identical. Evidently, with respect to its wavelength, the recoiling electron may be replaced by a scattering electron moving in the direction of the incident beam at a velocity such that:

$$\beta = \alpha / (1 + \alpha) \tag{8}$$

The formula βc is the "effective velocity" of the scattering electrons.

As already observed, Compton proposes that each quantum of *x*-rays is scattered by an individual electron. The recoil of this scattering electron, due to the change in momentum of the *x*-ray quantum when its direction is altered reduces the energy and hence also the frequency of the quantum of radiation. The corresponding increase in the wavelength of the *x*-rays due to scattering is:

$$\lambda - \lambda_0 = \delta(1 - \cos\theta)$$

where λ represents the wavelength of the ray scattered at an angle θ with the primary ray whose wavelength is λ_0, and

$$\delta = h/mc = 0.0242 \text{ Å}$$

5. Observations

Several pertinent observations concerning Compton's investigations are appropriate at this point. To begin with, in the best tradition of NS, Compton's research combines rigorous theorizing and experimentation within an accepted paradigm, Thomson's electrodynamics. The stepwise and systematic modifications of the large electron hypothesis are consonant with Kuhn's description of NS as a paradigm-guided, puzzle-solving activity in which mathematics is the major instrument of analysis. According to Kuhn, no paradigm (or theory) resolves all the puzzles it helps define. As we have seen, although the early experiments of Barkla and others support Thomson's classical theory, it fails to explain many of the more recent experiments involving spectroscopic examination of secondary *x*-rays from graphite. Classical electrodynamics predicts that the energy scattered by an electron bombarded with an *x*-ray beam of unit intensity is the same whatever may be the wavelength of the incident rays, and that when *x*-rays pass through a thin layer of matter, the intensity of the scattered radiation should be the same. Experiments confirm these predictions, especially for *x*-rays of moderate hardness scattered by light elements. When very hard *x*-rays are used, the scattered energy deviates significantly from the values predicted by the classical paradigm; that is, its value is less than the value predicted by Thomson's theory. Careful spectroscopic investigations of secondary *x*-rays scattered by graphite establish that only a negligible percentage of the secondary radiation has the same wavelength as the primary radiation, contrary to expectation based on the classical theory. These technical puzzles motivated Compton to look critically at the classical paradigm. Kuhn, as we already noted, recommends "extraordinary research" when an established paradigm fails to resolve a significant anomaly. Compton's revolutionary integration of light quanta into his equations to explain increase in the wavelength of *x*-rays after colliding with an electron fully conforms to that recommendation, the rationale being that the velocity of the recoiling electron is comparable to the velocity of light, and a quantum of *x*-rays impart its energy upon some particular electron.

Compton did not jettison completely the classical paradigm even after introducing the quantum hypothesis in his theoretical calculations—in fact, he was ambivalent about the relation between the classical theory and his radical quantum interpretation of particle scattering. In the *Proceedings of the National Academy of Sciences* (Vol. 9, 1923, 350-362), he maintained that the present quantum conception of diffraction is far from being in conflict with classical wave theory (Cohen, 431). Similarly, Roger Stuewer reports that Compton "himself scarcely recognized the creative break he had made with his past work and with the classical paradigm as well. Rather, in essence, he had simply tried something, and it had worked" (Stuewer 1976, 626).

Yet that same year, in a 1923 lecture to the American Association for the Advancement of Science (printed in 1924 in the *Journal of the Franklin Institute*), Compton explicitly stated that his discovery presented a revolutionary change in our ideas regarding the process of scattering of electromagnetic waves (Cohen, 431). Compton's reluctance to jettison classical electrodynamics completely (from which stems the ambivalence noted above) and Kuhn's principle of commitment to paradigm in NS have the same strategic epistemological justification, namely, that "every theory is fraught with anomalies, so that taking each such anomaly as a potential refutation would put an end to science" (Kuhn 1970b, 77-82).

7. Conclusion

Like other philosophers of science, Kuhn is keenly interested in elucidating science, the reason behind its special efficacy, and the cognitive status of its theories. Nonetheless, as he is at pains to stress, unlike most of them, he begins as a historian of science, paying special attention to the facts of scientific practice documented in scholarly historical work. Kuhn formulates a model of science that incorporates scientific behaviour which, according to the "received view," is aberrant and inessential to philosophical explanation of science. The engine of that model is what he called NS, a rigid and cumulative type of scientific research based on "paradigm." NS is the characteristic activity of scientists *qua* scientists; it is the feature of science that most differentiates it from other knowledge producing endeavors. Kuhn's conception of NS, when interpreted with proper safeguards against unnecessary exaggerations and ambivalent methodological claims, is a plausible account of how and why scientists have, to an astonishing degree, succeeded in achieving the central purpose of scientific research—the acquisition, consolidation, and extension of trustworthy knowledge of the world.

The first and second phases of Compton's research programme, as we have shown in this paper, bear the hallmarks of NS. Compton is a conservative physicist committed to the principles of classical electrodynamics as paradigm. His research findings eventually precipitated anomalies that led to the overthrow of that very paradigm. Compton's quantum interpretation of *x*-ray scattering gave new direction to the investigations of radiation. His conservative attitude to classical electrodynamics despite growing anomalies is consistent with the attitude of tenacity to paradigms Kuhn emphasizes in NS. However, contrary to the controversial view canvassed by Kuhn regarding the function of dogma in scientific research, Compton's unwillingness to jettison the classical theory is not dogmatic. Rather, it is the result of reasoned conviction, stemming from previous successful applications of the theory, that classical electrodynamics would eventually resolve the technical puzzles connected with observed changes in the wavelengths of the primary and secondary radiation during *x*-ray scattering experiments. Therefore, Compton could not have changed from a classical to a revolutionary quantum physicist overnight. As his research progressed, he realized that a novel approach was required for resolving anomalies that emerge in sophisticated scattering experiments.

Despite the fact that initially some physicists vacillated concerning the revolutionary import of his findings (Stuewer 1975, Ch. 6), Werner Heisenberg is one of the earliest scientists in the physics community who recognized that the effect eponymously named after Compton marks a turning point in scientific understanding of the scattering of electromagnetic radiation (Stuewer 1975, 287). Without a doubt, as the analysis above demonstrates, the Compton Effect is the culmination of a very high-class piece of normal research on x-ray scattering.

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