



A man of Germany : acceptable uncertainties in a time of war
by John Bernard Gallagher II

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Art's in History
Montana State University

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Abstract:

During the week of September 15, 1941, Niels Bohr and Werner Heisenberg met secretly in Copenhagen, Denmark. These Nobel physicists worked together in the 1920s to construct a new quantum physics. The Copenhagen Interpretation consisted of statistical quantum mechanics, the Uncertainty Principle, and Complementarity, which revolutionized perceptions of atomic phenomena and challenged the scientific community with their conceptions of classical Newtonian causality. At the time of the meeting, Germany occupied Denmark and Heisenberg led the German effort to develop practical applications of nuclear fission. Bohr's and Heisenberg's meeting ended with anger and frustration leading to the separation, personally and professionally, of these two men. Owing to a lack of documentation and the varying opinions over the events of 1941, I propose to use the scientific principle of uncertainty, developed by Heisenberg in 1927, as a metaphor to broaden our understanding of the meeting between these men. Instead of using the two pairs of conjugate variables, as defined by the Uncertainty Principle, I will use four-square variables that allows for an alternate interpretation of the 1941 Bohr-Heisenberg meeting. The four-square variables involve aspects of Werner Heisenberg's life. These are the development of his scientific work, the formation of the scientific community through collaboration, the social, cultural, and political context of Germany, and the personal and professional relationship between other physicists and between Bohr and Heisenberg themselves. My thesis seeks to determine what was said between these men that led to the disruption to their relationship. My conclusions limit the indeterminacy of the event and brings a level of acceptable uncertainties that illustrate above all that Heisenberg was a man of Germany

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MONTANA STATE UNIVERSITY
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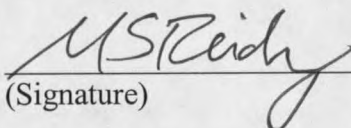
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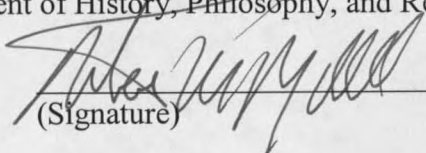
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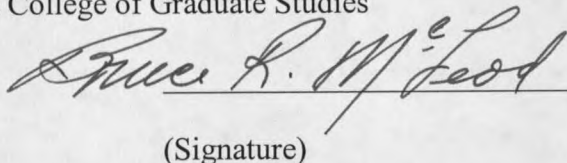
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DEDICATION

For my Wife, Carol Rae,

There are strengths and weakness associated with my intense study of Werner Heisenberg, the community of quantum scientists, and the troubled Weimar and Third Reich years. Due to my desire to acquire a degree in education, my "school years" have stretched further than either you or I first anticipated. I am sure that when I left Triad you were happy that we both would work in the teaching field together. You have supported, helped, and encouraged me throughout both graduate programs. Your patience with my extremely long sentences, numerous prepositions, too many books and journals spread all over our house, and a few, not many, cancelled or shortened trips have been monumental. I appreciate you as my friend and love you as my wife. Affectionately yours,

John

For my parents,

My gratitude and debt to you reaches far beyond any words I can bring forth. Your love and support encouraged me to accomplishment anything I have desired. Throughout my journey you have constantly shown your love and direction for me. I am truly privileged to have such wonderful parents as you. That someday I am able to repay all that you have given to me, and that you, Rosemary and Jack Gallagher, may feel proud of the following work, is the affectionate wish of your youngest and only son,

John

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ABSTRACT

During the week of September 15, 1941, Niels Bohr and Werner Heisenberg met secretly in Copenhagen, Denmark. These Nobel physicists worked together in the 1920s to construct a new quantum physics. The Copenhagen Interpretation consisted of statistical quantum mechanics, the Uncertainty Principle, and Complimentarity, which revolutionized perceptions of atomic phenomena and challenged the scientific community with their conceptions of classical Newtonian causality. At the time of the meeting, Germany occupied Denmark and Heisenberg led the German effort to develop practical applications of nuclear fission. Bohr's and Heisenberg's meeting ended with anger and frustration leading to the separation, personally and professionally, of these two men. Owing to a lack of documentation and the varying opinions over the events of 1941, I propose to use the scientific principle of uncertainty, developed by Heisenberg in 1927, as a metaphor to broaden our understanding of the meeting between these men. Instead of using the two pairs of conjugate variables, as defined by the Uncertainty Principle, I will use four-square variables that allows for an alternate interpretation of the 1941 Bohr-Heisenberg meeting. The four-square variables involve aspects of Werner Heisenberg's life. These are the development of his scientific work, the formation of the scientific community through collaboration, the social, cultural, and political context of Germany, and the personal and professional relationship between other physicists and between Bohr and Heisenberg themselves. My thesis seeks to determine what was said between these men that led to the disruption to their relationship. My conclusions limit the indeterminacy of the event and brings a level of acceptable uncertainties that illustrate above all that Heisenberg was a man of Germany

CHAPTER ONE
COPENHAGEN, 1941

Introduction

In September 1941, Werner Heisenberg and Carl Friedrich von Weizsäcker traveled to Denmark to give follow-up talks to the Danish physics community. Because of a previous, highly successful talk in Copenhagen, Weizsäcker was invited back with Heisenberg, to attend a conference on mathematics, astronomy and theoretical physics given by the German Cultural Institute based in Copenhagen, Denmark. Weizsäcker initiated an invitation to Heisenberg, as they both could visit with their previous tutor, Niels Bohr.¹

During the week of September 15, 1941, Niels Bohr and Werner Heisenberg met secretly. Their conversation is unknown because neither of these men recorded their conversations nor took any notes. At the time, Heisenberg led one of Germany's atomic bomb projects. His Leipzig group found evidence of neutron multiplication in a reactor. This discovery suggested that a chain reaction was a distinct possibility and that a practical application of nuclear energy was likely. Bohr's work on fission placed him as an authority on practical applications of particle physics. Bohr, living in Nazi occupied Denmark, received Heisenberg as a guest and fellow collaborator in the development of quantum theory. The importance of this meeting between these two prominent nuclear

physicists lies in the influence it had upon both their futures. However, their meeting ended with frustration, anger, and disappointment for both men, each one taking away different interpretations of the meeting.²

In a 1956 interview with journalist Robert Jungk, Heisenberg discussed the 1941 meeting between Bohr and him. One year later, Bohr drafted a letter to Heisenberg that conveyed his disappointment by saying, "I am amazed to see how much your memory has deceived you" Bohr continues,

Personally, I remember every word of conversations, which took place on a background of extreme sorrow and tension for us here in Denmark. In particular, it made a strong impression both on Margrethe and me...that you and Weizsäcker expressed your definite conviction that Germany would win...I also remember quite clearly...you spoke in a manner that could only give me the firm impression that, under your leadership, everything was being done in Germany to develop atomic weapons...³

Though this letter was never sent to Heisenberg, Bohr's feelings of anger and frustration were supported by a comment he made a few years later to a fellow Russian associate, as told by Mark Walker in "Werner Heisenberg's Foreign Lectures under National Socialism":

Heisenberg wanted to convince his mentor that Hitler's victory would be inevitable...The Nazis did not honor his science...Heisenberg and Bohr had to join forces and help Hitler, and then, when he was victorious, his

¹ Mark Walker, "Werner Heisenberg's Foreign Lectures under National Socialism," *Historical Studies in the Physical Sciences*, Vol. 22, part 2, (1992): 339; 362.

² David Cassidy, *Uncertainty: The Life and Times Of Werner Heisenberg* (W. H. Freeman and Company, 1992), 435-8.

³ Niels Bohr Institute, Copenhagen, Denmark. Niels Bohr Archive Paper Documents. The documents were retrieved from www.nbi.dk/NBA/papers/docs/d01tra.htm (3/13/2004). A series of eleven original documents from Niels Bohr's personal family collection were released to the public. The first document is a reaction to Heisenberg's interview with writer and journalist Robert Jungk for his book "Brighter than a Thousand Suns." Documents 2-5 are correspondences between Heisenberg and Bohr on Heisenberg's sixtieth birthday celebration. Documents 6-10 are had written and draft letters to Heisenberg over large topics in their personal history. Documents 11a and 11b address, specifically, the 1941 meeting in detail.

attitude towards scientists would change.⁴

However, Heisenberg's interpretation of the heated discussion differed. In a letter written to his wife, Elizabeth, explaining his Copenhagen visit, he used casual speech: "Bohr and family are doing fine; he himself has aged a little, his sons are fully grown now."⁵ He wrote positively, reflecting on his friendship with Bohr and fond remembrances of Copenhagen in his youth. Only twice in his two-page letter did he mention anything that bordered on controversy: "The conversation quickly turned to...unhappy events...Bohr can not separate out thinking, feeling, and hating entirely...During the unavoidable conversations, where it naturally and automatically became my assigned part to defend our system."⁶

In a letter Bohr wrote to Heisenberg some years later, a change in Bohr's tone is evident. His introduction was cordial and the words were congenial and friendly. Bohr did not blame Heisenberg for working with the Nazis or accuse Heisenberg of evil and manipulative intentions at their 1941 meeting. He merely asked for Heisenberg's input on what he remembered of that meeting in Copenhagen. The overall tone had changed from earlier letters that expressed Bohr's frustration and anger over Heisenberg's public statements about their 1941 meeting.⁷

⁴ Walker, "Werner Heisenberg's Foreign Lectures," 366.

⁵ The Manhattan Project Heritage Preservation Association, Inc. Archives. A hand-written letter to Elizabeth Heisenberg from Werner Heisenberg from Copenhagen, Denmark on September 1941. The document can be viewed at www.werner-heisenberg.unh.edu/Copenhagen.htm.

⁶ Ibid.

⁷ Niels Bohr Institute, Copenhagen, Denmark. Niels Bohr Archive Paper Documents. The documents were retrieved from www.nbi.dk/NBA/papers/docs/d11atra.htm (3/13/2004).

Over the years both men's memories changed their interpretation over this meeting and the private words that were spoken as the two men's lives and perspectives changed. The conflict is apparent in the guest log of Bohr's institute, and notes that Heisenberg, who had been a regular visitor, was absent from the Copenhagen institute for well over a decade. What actually transpired that September day? Unfortunately, because of the lack of documents and the participants' failing memory, we can never know with complete certainty.

Histiographical Analysis

The academic background and personal experiences of scientists and historians who have written about Neils Bohr and Werner Heisenberg affected their analysis and interpretation of the 1941 secret meeting and Heisenberg's capability to build an atomic bomb. Initially, scientists that worked for the Allied post-war effort and historians both viewed Heisenberg as a traitor towards science. However, scientists and historians with ties to Germany and contemporary historians interpret Heisenberg's actions with a more sympathetically and conjecture that Heisenberg's group's intellectual breadth and technological capacity was not sufficient to develop a working atomic bomb for the Germans. Scholarship and public opinion has evolved through the decades since the war. Post-war reconstruction, discovering Hitler's "final solution," the cold war struggle between the U.S.S.R and the United States, the deaths of Bohr and Heisenberg, and the recent releases of personal letters all shaped these changing opinions.

Samuel Goudsmit's *Alsos*, published in 1947, told the story of the Allied mission to gather and examine papers relating to the German effort to build an atomic reactor and bomb.⁸ The book determined the reasons for Germany's failures as well. The commission headed by Goudsmit concluded that Germany's bomb program failed for two reasons. First, German state officials were too involved in matters of science that they did not sufficiently understand the creation of science, thus sabotaging the efforts of the scientists. Second, Heisenberg himself made gross errors in calculating the critical mass of radioactive materials, a key element in the creation and production of an atomic bomb. Goudsmit further speculated that Heisenberg's supposed moral scruples, about creating the bomb were only a charade to cover the fact that he made gross errors in critical mass calculations for U235.

Goudsmit, an old friend and colleague of Heisenberg from the German physics community in the 1920s, wrote in a bitter tone through circumstances of his own personal tragedy. During his investigations, he found that both his parents died in Hitler's concentration camps. He dismissed Heisenberg as arrogant and hostile to any questions from the commission. Even after publication of his book, he continued to discredit Heisenberg and all German scientists that worked on the bomb for Hitler. The immediacy of writing *Alsos* colored Goudsmit's judgment and the historical analysis he brought to the evidence. With emotional distance between him and the actions of those German scientists, Goudsmit moderated his critical evaluation of Heisenberg in later years.

⁸ Samuel A. Goudsmit, *Alsos* (Henry Schuman Inc, 1947), xiv, 3-259.

Journalist Robert Jungk interviewed Heisenberg to write *Brighter than a Thousand Suns*, a 1956 popular account of the German scientists involved with the German bomb project.⁹ *Brighter than a Thousand Suns* is the earliest attempt to defend Heisenberg and his actions during the Third Reich. Jungk maintains that German scientists participated in the bomb effort to actively withhold vital information on the development of the atomic bomb. He supports his argument primarily on a long interview with Heisenberg, who told him, "...under a dictatorship active resistance can only be practiced by those who pretend to collaborate with the regime. Anyone speaking out openly against the system thereby indubitably deprives himself of any chance of active resistance."¹⁰ Jungk later changed his opinion of Heisenberg and reverted to a critical view of the bomb program and Heisenberg's involvement. Jungk was not the only author to change his mind.

David Irving interviewed Heisenberg as research for the *Virus House (The German Atomic Bomb)*.¹¹ Irving's focus differed from the other authors. Irving argued that these scientists were concerned primarily with their current research and the future prospects of their science. Arguments of morality, German culture, and Third Reich politics are relatively unimportant in the book. Instead, Irving stipulated that these

⁹ Robert Jungk, *Brighter Than a Thousand Suns: A Personal History of the Atomic Scientists* (Harcourt, Brace, & World, Inc, 1956), xiv, 1-369.

¹⁰ As quoted in Michael Frayn's postscript in *Copenhagen* (Michael Frayn, *Copenhagen* (Anchor Books, 1998), 110-1.

¹¹ David Irving, *The German Atomic Bomb: The History of Nuclear Research in Nazi Germany* (Simon & Schuster, 1967), 1-329. In 1967, David Irving originally published his book on the German bomb program as the *The Virus House* in Great Britain. One year later, his American publisher's Simon & Schuster changed the title to *The German Atomic Bomb*. The English title of Irving's book spoke to the name the German's gave to the facility they used to conduct their uranium experiments on radioactive cylindrical

scientists modeled their apolitical nature after the late nineteenth-century German scientists in their drive for science. The group solely concerned itself with how to continue their research.

Irving's argument is strong. Certain variables, however, are left out of the equation required to understand Heisenberg and his associates. To examine but one variable of Heisenberg leaves too many unanswered problems within the context he and his fellow scientists found themselves.

In *Albert Speer: His Battle with Truth*, Gitta Sereny focused on two issues critical to understanding Heisenberg.¹² Her book does not analyze Heisenberg but Albert Speer, the commander of the German Air Force with whom Heisenberg had several high level and secret meetings. She asks why did Heisenberg in 1942 request so little funding from Speer and his military associates. She argues that he had an objection to the final outcome of the bomb and tried to postpone the development. However, she later argues that Heisenberg's intent at Copenhagen was to convince his mentor of Germany and Hitler's ultimate victory. Her aim is to tell Speer's story and not Heisenberg's. Her sources mainly come from Speer and his collaborators, and her text provides a one-sided view of Heisenberg's true intents and actions.

In *Hitler's Uranium Club* written after secret recordings at Farm Hall were declassified, Jeremy Bernstein clarifies these transcripts and the issues that surrounded

reactor models. The building was housed on the Kaiser Wilhelm Institute for Biology, thus the name of their building kept would be investigators or curious people away (Cassidy, *Uncertainty*, 428).

¹² Gitta Sereny, *Albert Speer: His Battle with Truth* (Vintage, 1995), 1-757.

the recordings.¹³ Bernstein uses his physics background to read between the lines of these transcripts and to understand the mental state of these ten captive German scientists. These transcripts unique value lie in the deep insight into how and why these men believed what they did during and after the war.

The Farm Hall secret recordings taped the conversations of the Germans scientists interned at a country manor, Farm Hall, outside of Cambridge, England. At the end of World War II as the Allied forces advanced, German scientists working on the atomic bomb were captured and interned, incommunicado from all who knew them at Farm Hall. Bernstein carefully prepares the reader to understand the German conversations with thoughtful and expert introduction to the scientific material and arguments of past critics. Bernstein concludes that Hahn, Heisenberg, and others “knew very little” regarding the nuclear physics needed to prepare, construct, and explode an atomic bomb¹⁴ What they did know came only after the 1945 explosions in Hiroshima and Nagasaki.

The problem with evaluating these transcripts, though they are valuable in deciphering German thoughts and actions, lies in what was recorded, transcribed, translated, and even lost or discarded. The Farm Hall transcripts only include about ten percent of the conversations among the German scientists. The German originals are no longer available nor are the actual recordings, since they were recycled after the transcriptions and translations were written.

¹³ Jeremy Bernstein, *Hitler's Uranium Club: The Secret Recordings at Farm Hall* (American Institute of Physics, 1992), xxx, 1-427.

¹⁴ Bernstein, *Hitler's Uranium Club*, p. x.

In 1984, Werner's wife, Elizabeth Heisenberg, made a personal and emotional plea through her book, *Inner Exile*.¹⁵ Her memoirs illuminate and focus our attention on Heisenberg's politics, scientific work, the world that intruded on his peace, and his multifaceted personality. She addressed public questions and comments of her husband, "...the various, sometimes almost obtrusive ideas of my husband's role that surfaced in the course of these discussions made me aware of how hazy, distorted, and quite false and contradictory people's notion were."¹⁶ Elizabeth Heisenberg shed valuable light on, and revealed an intimacy with, her husband that the greater academic community would not have been privileged to. However, it is just that intimacy that warns the rational and critical evaluator that this type of personal defense is subject to question and verification.

In 1993, Thomas Powers wrote *Heisenberg's War* to examine Heisenberg's reticent attitude towards his involvement in the German bomb program.¹⁷ Powers argues that a retrospective of Heisenberg's intentions and actions are hard to evaluate based on the political pressure and the horrific crimes of war. Powers' answer unraveled military and personal secrets. He tries to evaluate and understand how these men struggled with their professional and private ethics and conscience.

Questions arise when assessing Heisenberg's motivation after the war. In his position, Heisenberg had two different communities to address. He did not want to appear to the German people that he lost the war and was a traitor. Nor did he want the

¹⁵ Elizabeth Heisenberg, *Inner Exile: Recollections of a Life with Werner Heisenberg* (Birkhäuser, 1984), xvii, 170.

¹⁶ Heisenberg, *Inner Exile*, 1.

¹⁷ Thomas Powers, *Heisenberg's War: The Secret History of the German Bomb* (Alfred. A. Knopf, 1993), xii, 3-610.

international scientific community to remember him as a collaborator with Hitler. Heisenberg, Powers argues, found himself in contradictory situations that make true analysis of his motivations and intentions difficult. Powers stipulates that three main factors can help in determining Heisenberg's true motivation for his Third Reich work. First, he had an obligation to his German graduate students and a responsibility to rebuild German science. Second, Heisenberg's motivation when visiting Bohr in 1941 was to offer him sanctuary in return for helping with the German bomb project. Third, Heisenberg never joined Hitler's party, but helped many friends in political trouble to escape Germany. Powers focused on the failure of Heisenberg's team based on their unwillingness to arm Hitler with atomic weapons, as the Allied Manhattan Project had unbridled enthusiasm to create a weapon of force to stop Germany and Japan. He makes the bold assertion that not only did the team not want to help Hitler, but they killed the mission itself.

Problems exist with Powers' scholarship. His argument is strong when evaluating Heisenberg's intention, motivation, and action. However, deciding that Heisenberg and his team killed the atomic bomb program is more uncertain. Powers does not analyze deeply enough Heisenberg post-1940 meetings with top military and S.S. officials regarding funding and prospects for practical applications of nuclear fission. Without investigating such high-level meetings, Powers cannot determine Heisenberg's true intention. Powers had an interesting idea of intention to action and should have followed up on the intentions of Heisenberg's efforts to secure high-ranking approval of his projects.

Another historian sympathetic to Heisenberg, Paul Lawrence Rose, wrote *Heisenberg, German Morality, and the Atomic Bomb* in 1984 and *Heisenberg and the Nazi Atomic Bomb Project: A Study in German Culture* in 1998.¹⁸ The second work builds on the first journal article to mount a defense and an understanding of why a scientist would attempt to help build a bomb for Hitler. Rose argues that these scientists would not build the bomb for Hitler but for Germany. Rose states,

But in the same year Hitler came to power, and though Heisenberg might well have preferred not to think about him, Hitler opened the door to a *crise de conscience* for German physicists...should we stay on and keep quiet...or was open protest...a viable alternative?¹⁹

To understand Rose's conclusion, one must understand German culture in the context that these scientists made their decisions about war and morality. Rose maintains that Heisenberg's science "must be set firmly in the German cultural climate and social context in which he always saw himself firmly situated."²⁰ He concludes that Heisenberg's arrogance and miscalculation is directly related to German culture. While, aspects of Heisenberg's personality definitely are derivative from German culture, but to equate his failings solely to culture misses Heisenberg's own failings with mathematical and experimental calculations. Throughout Heisenberg's academic career, he made calculations that were off by a small amount but significant and lacked detail in

¹⁸ Paul Rose, *Heisenberg and the Nazi Atomic Bomb Project: A Study in German Culture* (University of California Press, 1998), xx, 1-352.

¹⁹ *Ibid*, xv.

²⁰ *Ibid*, p. xvi.

constructing experiments.²¹ Rose is an enthusiastic supporter of Heisenberg, but avoids points that illuminate problems with his professional work.

Most recently, David Cassidy published, *Uncertainty: The Life and Science of Werner Heisenberg*.²² Cassidy's monumental biography of Heisenberg attempts to create an overall picture of his life, work, and the society and culture in which he lived. Cassidy argues for Heisenberg's great contributions to science and the unique position he found himself in during the early years of the Third Reich, but Cassidy does not focus on the Bohr-Heisenberg meeting of 1941 (two pages of a 545 page book) nor Heisenberg's involvement in the German bomb program. Recent scholarship had focused heavily on the 1941 meeting, and to avoid these issues taints the larger volume.

In 1998, Michael Frayn wrote *Copenhagen*, a play that explored the secret meeting of these physicists.²³ The play cleverly exploits parallels between human psychology, questions raised by internal history, and a value system constructed within social and cultural forces. He complicates the historical record with philosophical and existential analogies between quantum mechanics and human existence. Through *Copenhagen*, he explores the limits of knowledge, of others, of oneself, and of the external world. He argues that arriving at definitive moral judgments is difficult, perhaps impossible.

As a work of fiction, Frayn's work cannot incorporate all the historical material relevant to evaluating the Heisenberg-Bohr meeting. However, this is not his objective,

²¹ The errors in calculation and experimental details do not encompass the war effort regarding atomic weapons with the large error in calculating fissionable uranium.

²² Cassidy, *Uncertainty* xii, 1-669.

although Frayn's extensive historical "PostScript" illustrates the scholarship and technical matters needed to understand his play. His work addresses the issue of how we, as individuals, understand a historical event.

To comprehend what either of these men were thinking is problematic, though many authors obviously have tried. Additionally, these authors have focused on the individual, Werner Heisenberg, and the 1941 secret meeting. From the end of World War II, through the post-war and Cold War period, and up to the publication of *Copenhagen*, the interpretation of these events has evolved. The conclusions are as diverse as their authors, depending on their unique perspectives. Indeed, two of the authors reverse their positions. Their work can best be understood through the various social, political, and cultural ideologies of their time. Each period of history has unique elements that affect the author's interpretation of the Bohr-Heisenberg meeting.

The Uncertainty Principle as a Historic Tool

Owing to a lack of documentation and the varying opinions over the events of 1941, I propose to use the scientific principle of uncertainty, developed by Heisenberg in 1927, as a metaphor to broaden our understanding of the meeting between these men.

The principle states,

$$\Delta p * \Delta q \geq h/2\pi$$

$$\Delta E * \Delta t \geq h/2\pi$$

²³ Michael M. Frayn, *Copenhagen* (Anchor Books, 1998), 3-135.

where p and q , and E and t are conjugate pairs. Conjugate pairs limit the extent to which a measurement, say momentum, can be separated from its conjugate pair, position; and the same is true for position in terms of momentum. To comprehend the relation, one must understand that if an experimenter adjusts the instruments to attain 100 percent accuracy for position, then the uncertainty of momentum increases to infinity, and *vice versa*.

Instead of using the two pairs of conjugate variables, as defined by the Uncertainty Principle, I will use four-square variables that allows for an alternate interpretation of the 1941 Bohr-Heisenberg meeting. During the late 1920s, the instruments available to the scientists limited the accuracy of their experiments. Physicists like Heisenberg, therefore used thought experiments. He hypothesized the Gamma ray microscope to simulate a photon measuring an electron's position. Unfortunately, before Heisenberg could register the position, the electron could have recoiled from impact with the photon. Heisenberg narrowed the field of vision to only register position, and in consequence, he lost any momentum measurement. As in Heisenberg's Gamma ray microscope though experiment, as the observer pulls the field of the microscope's vision to a broader range, the uncertainty is minimized for all variables. Therefore, for our purposes, if the historian tries to obtain accuracy for the individual event that occurred in 1941, from only one perspective the result will be total uncertainty. However, like the experimenter, if we pull back our field of vision and examine the other four-square variables involved, the picture will emerge with acceptable uncertainties. The four variables involve aspects of Werner Heisenberg's life. These are the development of his scientific work, the formation of the

scientific community through collaboration, the social, cultural, and political context of Germany, and the personal and professional relationship between other physicists and between Bohr and Heisenberg themselves.

Important to this analysis with each of these variables is the idea of motives, intentions, and actions of those involved. These facets of the variables shape the individual through contradictory pressures from outside and within the individual. This analysis parallels the theoretical uncertainty proposition by the systemic limitation these variables impose over understating human events. By incorporating the ideas stated in the Copenhagen Interpretation, one realizes that to determine anything about human events, the event, no matter how objective, is affected by the human observer. The act of analyzing a past event introduces uncertainty and subjectivity of the human mind. My argument does not reduce error to absolute certainty; rather, the model takes into consideration broader variables that affected the individual events and brings a greater precision to analyzing the 1941 meeting.

Chapter Outline

A number of researchers have analyzed Heisenberg's involvement with the German bomb program and his 1941 meeting with Niels Bohr in Copenhagen. Some of these authors wrote decades ago and their views were impacted by either the horrors of World War II or the Cold War. Other authors, with the benefit of newly released documents, have widened our view of Heisenberg and his fellow scientists. However, with time memories become vague and problematic towards finding certainty.

My approach using Heisenberg's uncertainty principle as a metaphor allows for a fuller approach to understanding Heisenberg, by tying together critical cultural, scientific, and political factors. To avoid complete and infinite uncertainty, each variable is essential; they can not be viewed exclusively and independently from each other. Each chapter examines the essential characteristics of each variable. To provide a clearer picture of each of these critical elements, taken as a whole, these elements eliminate some of the uncertainty and create some confidence of what transpired at the 1941 meeting between Bohr and Heisenberg.

The second chapter, "Theoretical Foundations of Quantum Theory," provides the technical and conceptual background of particle physics. Beginning with the mathematization of Planck's constant, the chapter connects significant developments that led to the theoretical framework necessary for the revolutionary discoveries of Heisenberg's Göttingen group and Schrödinger's wave mechanics. After the initial discoveries were made, these groups working collaboratively, stressed the creative and imaginary, broke with classical causality, and challenged the world with the Copenhagen Interpretation.

The next chapter, "Heisenberg and the Turmoil of the Weimar Republic," examines forces outside of Heisenberg's control that applied great pressure on his life and others around him. Social, cultural, and political factors influenced Heisenberg's actions and ideologies. The romantic history of Wilhelmian Germany, the devastating experiences and defeat of World War I, the troubled and chaotic years of the Weimar Republic, the rise of a new political party in the ashes of the Weimar democratic

government, and the Aryan challenge to Heisenberg's sense of nationalism and modern "Jewish" physics all affected the formation of Heisenberg's character and personality, ultimately shedding light on the fateful evening of September 1941.

Chapter four, "Solitary Genius," focuses on the three great groups involved with the rise of quantum theory (Göttingen, München, and Copenhagen) and their interaction with each other in the process of creating science and the scientific community. These research institutes, because of the intense nature of quantum theory, needed to expand and create a community that transcended national borders. Collaboration was absolutely essential for their endeavor. The chapter title, "Solitary Genius," belies the actual thesis, because the individual creating breakthrough science is a myth. The chapter illustrates this thesis by examining the construction of collaborative communities, the leaders that recruited and directed the talented individuals, and the three-man paper published by Max Born, Werner Heisenberg, and Pascual Jordan that revolutionized the quantum theory.

The concluding chapter, "A Perfect Union of Mentor and Student," deviates from current scholarship by questioning the relationship between Bohr and Heisenberg as a father and son or mentor and student. Though Bohr was a mentor for Heisenberg and even guided him during his most productive years, a tension and aggressive nature existed between the two. My readings and interpretation of the Archives for the History of Quantum Physics expressly show that Heisenberg was an outsider and was not thought of as fondly as Bohr's other assistants. The strained relationship between Bohr and Heisenberg and even other associates of Heisenberg open up a completely different aspect

of his personality. His personality, quick to anger and frustration, estranged many physicists.

CHAPTER TWO

THEROETICAL FOUADATIONS OF QUANTUM THEORY

Introduction

Imagine climbing a mountain cliff. At the bottom of the cliff, the height overwhelms you. No amount of work and enthusiasm, it seems, could ever overcome this objective. The climb begins at the start of the cliff and nowhere else. The first objective rises several hundred meters above with the formation of a small pillar. The key to climbing the pillar is solved and your team prevails. The initial climb, however, does not get you to the top. The summit is separated by several additional obstacles that your group first must overcome. Not every action taken is necessarily significant, but surmounting the smaller objectives will lead to the summit. Once these obstacles are linked together, a path towards the summit becomes visible for the party.

The practice of science entails a similar journey. Theoretical revolutions in science are based on the previous work and contemporary collaboration among scientists. The revered German scientist, Max Planck, while lecturing on the development of physics, stated "In the history of science a new concept never springs up in its complete and final form as in the ancient Greek myth, Pallas Athene sprang up from the head of Zeus."¹ Instead, the concept develops slowly with minute contributions that enhance the

¹ Werner Heisenberg, "Development of concepts in the history of quantum theory," *American Journal of Physics*, Vol. 43 no. 5 (1975): 125.

current theory in a collaborative effort of modification and motivation until a comprehensive formalism structures all the elements.

Planck's observation has meaning when examining the development of quantum theory. Before the discovery of matrix and wave mechanics, theoretical developments and insights into atomic structure advanced our understanding of the atomic structure yet did not lead to a full and comprehensive description of quantum phenomena. To appreciate Heisenberg and Schrödinger's work, one must know the previous developments, the characters involved, and the processes that led to current advancement.

A climber cannot accomplish feats without the assistance of those around him or her. They rarely work alone on a mountain but often need the encouragement and help of fellow climbers. This is true in the scientific community as well; upon examination, the myth of the solitary genius collapses. Scientists use each other for inspiration, motivation, collaboration, and direction towards a goal the community as a whole adopts. To understand the importance and contributions of Heisenberg, Bohr, and Schrödinger to the theory of quantum mechanics in the Copenhagen Interpretation, one must examine and understand the developments of quantum theory and those physicists who contributed, helped, and expanded Heisenberg's and Schrödinger's revolutionary insights into a complete mathematical formalism of matrix mechanics and wave mechanics.²

Turn of the century discoveries, including J.J. Thompson's electrons, Rontgen and Becquerel rays, Curie's radioactivity research, and Rutherford's work on atomic disintegration, resulted in phenomena that did not correspond to classical explanations of

² The Copenhagen Interpretation has been referred to in the work of Bohr and Heisenberg (Complimentarity and the Uncertainty relations, respectively) but a few scientists and historians include an additional interpretation on atomic events developed by Born with his statistical interpretation of wave mechanics.

physical events. These events challenged the contemporary idea that all knowledge had been discovered and that nothing was left to find. At the turn of the century, blackbody radiation, the photoelectric effect, spectra lines and the X-ray scattering all frustrated physicists because these phenomena could not be explained within a framework of classical physical.³

Saving the Phenomena

Max Planck's work challenged and motivated the physics community to explain the turn of the century discoveries. Planck was born in Kiel, Germany on April 23, 1858. After completing elementary school in Kiel, the family moved to München, where Planck entered *Königliche Maximilian Gymnasium*. He proved to have talent in mathematics and his instructors introduced him to various problems in astronomy, mechanics, and thermodynamics. The principles of the conservation of energy made a strong impression on this young student and later led to his great achievements in the field. After matriculating at the University of München, Planck pursued the study of physics over pure mathematics to ponder these questions. His first recognized success came with a paper, *Gleichgewichtszustände isotroper Körper in verschiedenen Temperaturen*, on the mechanical theory of heat. He extended the theory by emphasizing the concept of entropy to evaluate elastic bodies being acted on by varying temperatures. Throughout his academic career, centered at the University of Berlin, he surrounded himself by, and was a member of, a gifted circle of scientists. Planck worked throughout his life on

³ Emilio Segré, *From X-rays to Quarks: Modern Physicists and Their Discoveries* (W. H. Freeman and Company, 1980), 1-45.

thermodynamics, radiation theory, relativity, and the philosophy of science. In 1918, after receiving the Nobel Prize, Planck stated, “an aim for me was to find the solution to the problem of the distribution of energy in the normal spectrum of radiating heat.”⁴ He was awarded the Nobel Prize in recognition for the discovery of energy quanta. Though German society revered Planck, as is evident with the many scientific institutions bearing his name, several tragedies befell his family through acts of the German state. During World War I, his youngest son, Karl died, and in 1944, an older son was executed by the S.S. for suspicion of plotting an assassination of Adolph Hitler. Later that year during an air raid, Planck lost all his personal and professional papers. He managed to outlive the war and died in Göttingen in October 1947.⁵

Planck introduced the idea of the “quantum of action” with a mathematization, h , which allowed the saving of the phenomena of blackbody radiation. A blackbody is a body that absorbs all electromagnetic radiation incident upon it. The absorption power of a blackbody is 100 percent.⁶ Experimental observations of wavelength emitted by blackbody radiation contradicted classical physical theory. Planck developed his quanta hypothesis while expanding on the experimental work of Wien, Rayleigh and Jeans. The problem with blackbody radiation was that it could not be explained by traditional thermal radiation theories, and the new Rayleigh-Jeans Law did not sufficiently model the thermal radiation exponential data.⁷ The theory exploded for short wavelengths and

³ Nobel Foundation, *Nobel Lectures: Including Presentation Speeches and Laureates' Biographies: Physics 1942-1962, Vol 1* (Elsevier Publishing, 1964), 407.

⁴ Charles Gillispie, ed., *Dictionary of Scientific Biography, Vol. XI* (Charles Scribner's & Sons, 1970), 7-17 and Nobel Foundation, *Nobel Lectures Vol. 1*, 402-20.

⁶ Emilio Segré, *From X-rays to Quarks*, 67.

⁵ $I(\lambda, T) = 2\pi^2ckT/\lambda^4$ refers to the energy distribution emitted by a blackbody under temperature flux (Thewlis, J. Ed., Vol. 6, p. 200).

high radiation intensities leading to theoretical contradictions.⁸ In 1900, Planck created an exponential model that fit the experimental data of blackbody radiation. Planck's model, at long wavelengths, simplified to the Rayleigh-Jeans Law but for smaller wavelengths, instead of exploding exponentially, his model decreased exponentially. Planck's expression, an exponential function, given by

$$I(\lambda, T) = 2mhc^2 / \lambda^5 (e^{hc/\lambda kT} - 1)$$

where h is referred to as Planck's constant, implied two bold postulates. Planck's constant, a numerical value, is derived by mathematical manipulation. The assumptions are key since their existence is not substantiated with any form of logic, mathematical formalism, or experimental observation. It was simply necessary to model the data successfully. Planck assumed that oscillating atoms emit or absorb, quantization, discrete energy called quanta and that these quanta have only discrete energy states.⁹ This last assumption was necessary to combat the experimental figures of the Rayleigh-Jeans Law.

The role assumptions play in science depends on the model that science itself creates and accepts. Models by themselves cannot be judged correct or incorrect. Rather, they can only be evaluated on a pragmatic continuum based on how well the data is represented and how the model predicts future events. This subjective scale assigns validity based on the models simplicity and approximation to real-world events. Assumptions impact, philosophically, science and society with the methods used by scientists. If the assumption creates a model that stands up to the logic of mathematics,

⁸ Raymond Serway, *Physics for Scientists and Engineers, with Modern Physics* (Saunders College Publishing, 1983), 1148.

⁹ Serway, *Physics for Scientists and Engineers, with Modern Physics*, 859-60.

then society's perception of reality conforms to the underlying assumptions of the model. Without experimental verification, our understanding of reality is changed or modified.

Discovering Lights Quanta

In 1905, Einstein endowed the quanta with physical qualities in relation to energy in the equation $E = nh\nu$. Einstein's paper explaining the photoelectric effect extended Planck's expression to electromagnetic radiation and furthered the attempt to explain the numerous unexplainable phenomena. Classical physics or the current wave theory of light did not adequately explain the photoelectric effect.¹⁰ The existing theory had four problems with this phenomenon.

1. Wave theory predicts that electrons are emitted at all frequencies and observations introduce a cut-off frequency that metals did not emit any electrons.
2. Values greater than the cut-off frequency introduce a proportional relation between the number of electrons and the light's intensity but experimental data, that wave theory can not explain, is that the kinetic energy of the phenomena is independent of the light's intensity, $I \propto f$, but not $K_{\max} \propto I$.
3. There is a proportional relationship between kinetic energy and the light's frequency, $K_{\max} \propto f$.
4. The photoelectric effect occurs immediately after the incident light strikes the surface. The contradiction lies in that classical theory stipulates a "charging-up" period in which enough kinetic energy is stored to emit electrons.¹¹

Einstein stressed that classical physics viewed light either as a particle or a wave and that his conclusions had to address this duality. Einstein insisted upon experimental verification, and the experimental results demonstrated that light must be treated as discrete streams of particles, Planck's quanta. Einstein further added that these discrete streams are bundled together, as discontinuous pockets, and that they maintain a relation

¹⁰ When light strikes metallic surfaces, electrons are emitted from those surfaces.

¹¹ Serway, *Physics for Scientists and Engineers, with Modern Physics*, 1151.

between energy, and Planck's constant and light's frequency, $E = hf$. Einstein worked out a further equation that explained the relationship between energy, the metal, electrons, and kinetic energy. His photoelectric effect equation is given by

$$K_{\text{max}} = hf - \phi$$

where ϕ is the work function of certain metals. In 1921, he labored on the photoelectric effect simultaneously with his more famous work on the general theory of relativity, but it was Einstein's work extending Planck's quantum concepts to solve the exponential criteria of the photoelectric effect that garnered him the Nobel Prize. This equation explains anomalies that classical physics did not. Einstein's work explained the four points that wave theory could not. The new quantum theory explained blackbody radiation and the photoelectric effect. However, two problematic phenomena remained, x-ray scattering and atomic spectra of elements.¹²

In 1923, Arthur Compton and Peter Debye followed Einstein's work on the photoelectric effect and conservation of atomic motion to solve the problems between classical physics and x-ray scattering.¹³ One assumption worked out by Planck and Einstein was that a ray of light transfers its intensity instantaneously to an electron, thus allowing no "warming up" period. In 1905, Einstein postulated that photons travel in bundles carrying momentum. In 1919, he added, "If a bundle of radiation causes a molecule to emit or absorb an energy packet hf [photon bundle], then momentum of quantity hf/c is transferred to the molecule..."¹⁴ Wave theory explained x-ray scattering

¹² Atomic spectral lines observed have frequency, intensity (brightness), and polarizations. The spectral lines are unique signatures of the various atomic elements (Cassidy, *Uncertainty*, 186).

¹³ Einstein assumed that during photon and electron collision atomic conservation of motion was preserved.

¹⁴ Serway, *Physics for Scientists and Engineers, with Modern Physics*, 862-3.

by a dependence on exposure to incident light and the radiation's intensity. Further, classical theory deduced that the initial frequency f_0 is greater than the resultant frequency. Thus, the impacted electron will oscillate and re-radiate less than the initial incident of light. Initially, Compton agreed with previous assumptions regarding x-ray scattering in his studies.¹⁵ The problem with these assumptions is that the electrons will take on a diameter that may be as large as the atom itself. Compton kept these assumptions because this large diameter electron model was successful in modeling the experimental data. For the next few years, Compton modified the model's structure.

Compton and Debye treated the incident as point-like particles, even though Einstein's assumptions created bundle-like quanta. This allowed them to derive an equation that modeled the experimental data. Their data refuted the previous claim that photon intensity and electron exposure were the causes of x-ray scattering. Instead, by assuming conservation of energy and momentum, and treating the bundles of light as singularities, their results showed that the shifted wave length λ_{Final} is dependent only on the scattering angle θ . Their results became known as the Compton effect derived from the Compton shift equation given by $\lambda_{\text{Final}} - \lambda_{\text{Initial}} = h/mc (1 - \cos \theta)$. Their published paper demonstrated that experimental data could be explained by a quantum and wave nature of light.¹⁶ Derivation of the Compton model involved many changes of assumptions. The Compton shift equation treated the photon with a mass of zero, at rest,

¹⁵ Roger Stuewer, "On Compton's Research," in *Essays in Memory of Imre Lakatos*, ed. R.S. Cohen, *Boston Studies in the Philosophy of Science*, Vol. 39 (1976): 619 and Arthur Compton, "A Quantum Theory of the Scattering of X-rays by Light Elements," *The Physical Review* Vol. 21, no. 5 (1923): 484. The formulation of Thomson mass scattering coefficient σ_0/ρ , assumes the following: 1.) Maxwell's equations are valid; 2.) the scattering electron is a point charge; 3.) there are no restraints on the scattering object; and 4.) all scattering electrons are independent of each other.

¹⁶ Stuewer, "On Compton's Research," 617-33 and Compton, "A Quantum Theory of X-rays by Light Elements, 501-2.

and energy, $E = hf = hc/\lambda$. Compton, in constructing his scattering model, assumed that conservation of energy and momentum was conserved. Applying this assumption to the scattering model gives the equation $hc/\lambda_{\text{Initial}} = hc/\lambda_{\text{Final}} + K_e$, where the first term represents the energy of the scattered photon and the second term is the kinetic energy of the recoiling electron. A relativistic modification must be taken into consideration because electrons travel at high speeds, thus changing K_e to $\gamma mc^2 - mc^2$.¹⁷ Compton states, “We thus have two independent equations...” after applying the laws of conservation to the x and y components of the collision.¹⁸ Using algebraic rationalization manipulates the two trigonometric equations to formulate the Compton shift equation.¹⁹

The Compton wave shift furthered the work of previous physicists, extended the existing theory with innovative assumptions, and helped to solidify and verify the new quantum theory within the scientific world by creating quantum models from real-world experimental data. A model requires verification of real-world data for it to be fully accepted by the scientific community.

Perplexing Atomic Spectra

At the turn of century, scientists could not explain the atomic spectra using classical physics.²⁰ Johann Jacob Balmer and his associates Briggs Lyman, Friedrich

¹⁷ The value $\gamma = 1/\sqrt{1-v^2/c^2}$

¹⁸ The equations is comprised of an x-component: $(hc/\lambda) = hc/\lambda'(\cos \theta + \gamma m v \cos \phi)$ and a y-component: $(hc/\lambda) = hc/\lambda'(\sin \theta - \gamma m v \sin \phi)$.

¹⁹ Compton, “A Quantum Theory of X-rays by Light Elements, 486-7.

²⁰ Atomic elements emit and absorb radiation that has a relationship with the electromagnetic spectrum. Many classifications exist that examine the various series of absorption and emission patterns that help identify atomic elements. The spectral lines consist of varied spacing of absorption (black) and emission (solid lines of varied width), which are a unique signature for each atomic element (J. Thewlis, eds., *Encyclopedic Dictionary of Physics: General, Nuclear, Solid State, Molecular, Chemical, Metal and*

Paschen, and Kelly Brackett derived equations for the spectral lines of hydrogen, but, none of these equations explained the spectra emission phenomena. In 1913, Niels Bohr, the Danish physicist who worked under J.J. Thompson and Ernest Rutherford, proposed the first quantum model of the atom and provided an explanation for the atomic spectral lines of less complex atoms and ions. He explained the stationary state of the atom by connecting three phenomena: stability of the atom, spectral laws, and the data collected by Ernest Rutherford's experiments. These phenomena contained the central concepts of the theory of the hydrogen atom.

1. The electron moves in circular orbits about the proton.
2. Only certain orbits are stable [no electron radiation]...the energy is fixed or stationary.
3. Radiation is emitted by the atom when the electron 'jumps.'
4. ...orbits are those for which the electron's orbital angular momentum about the nucleus is an integral multiple of $\hbar = 2\pi$.²¹

These concepts allowed Bohr to derive the electron's orbital path. The derivation had four essential assumptions: the electron is influenced by Coulomb's force of attraction; the frequency of emitted particle radiation, known as the photon, is independent of the orbiting electron; the emitted frequency is a relation between the atoms initial and final energies given by the Planck-Einstein formula $E_i - E_f = hf$; and X-ray emission, as seen in the atomic spectral lines, is the interaction of molecules that form atoms and the chemical properties inherent in that interaction.

Arguments for and against this mechanical model abounded within the scientific community. Positive experimental results involving hydrogen worked well. Material

Vacuum Physics, Astronomy, Geophysics, Biophysics, and Related Subjects Vol. 6 (Pergamon Press, 1961), 642-6.)

¹⁹ Serway, *Physics for Scientists and Engineers, with Modern Physics*, 1159.

evidence supported the Bohr model with the hydrogen lines by Sommerfeld and the splitting of lines in an electrical field by Stark, known as the Stark effect.²² However, problems arose when observing the frequency of orbits and the degeneracy of the atom in an electric field. Hydrogen was a simple case. Other, more complex elements posed greater obstacles in developing structured formulas for atomic theories.

Wolfgang Pauli stipulated that orbits such as helium would be too complicated to study and apply the rules of quantization developed by Bohr and Sommerfeld. Instead, he focused on the hydrogen ion because it had a stable and periodic orbit. Using classical mechanics, Pauli's theoretical results did not match the experimental data that predicted stationary states had specific energy levels. His results created doubt in using classical physics to define the energy levels associated with atomic orbits. Pauli's paper impacted the physics community by shifting their methodological approach to understanding atomic structures by analyzing the transitions between stationary states and exploring alternative methods of investigation other than classical mechanics.

Change in Focus and Method

This methodological shift turned to the transition probabilities of energy levels and the electrons orbital paths using theories developed by Einstein and Bohr, with the aid of Fourier expansion series.²³ In 1918, Bohr conceptualized that the transition event

²⁰ Johannes Stark applied external electric field to a source of light and recorded modifications to the atomic spectra. An asymmetric splitting appears different from the normal spectral images (Zeeman effect). This displacement is great and can be seen through a color shift in the visible portion of the spectra. This discovery was utterly unexpected and led to the development of this phenomenon as a tool for molecular rotational spectra (Thewlis, *Encyclopedic Dictionary of Physics Vol. 6*, 822-3).

²³ Fourier expansion series is a mathematical tool comprising differential equations to model complex real-world situations.

between classical and quantum laws happens during the cross over from small quantum numbers to large quantum numbers. His formula demonstrated a correspondence between every quantum condition²⁴ given by the expression $\tau_k = n'_k - n''_k$ ($k = 1, 2, 3, \dots$). The derivative of the frequency of light over time gives the final part of Bohr's principle $(4/3c^3(2\pi)^5 \nu_{\tau_1, \tau_2, \dots, \tau_s})^4 A_{\tau_1, \tau_2, \dots, \tau_j}$. The expressions determine the polarizations and intensities of spectral emission during a transition from one quantum state Q_1 to another state Q_2 .²⁵

Motivated by Bohr's Correspondence Principle, the physics community tried to help formulate and expand additional quantum laws. In 1923, Alfred Lande utilized Bohr's ideas to derive a formula for energy levels and to explain the 1887 anomalous Zeeman effect. Others helped address experimental difficulties with the data that contradicted Bohr's formal theory. This marked a new focus, away from the old quantum theory of stationary states and towards the progressive theories of dispersion and transitional probabilities. The larger scientific community realized Bohr's Correspondence principle as a necessary and essential part of examining the atomic structure in a different and revolutionary aspect.

The next integral step in understanding and visualizing the atomic structure came with Wolfgang Pauli's radical advancement of the Exclusion Principle.²⁶ Sommerfeld's fine structure suffered from a contradiction between observation and his theory, as can be seen when one applies his theory to sodium. A spectral analysis of sodium exhibits the

²² The quantum condition is a transition between energy levels that can be observed through intensities and polarizations of atoms spectral emissions.

²³ Thewlis, *Encyclopedic Dictionary of Physics Vol. 2*, 116-19.

²⁶ Wolfgang Pauli, "Über den Zusammenhang des Abschlusses der Elektronengruppen im Atom mit der Komplexstruktur der Spektren," *Zeitschrift für Physik*, Vol. 31 (1925): 765-83.

sodium doublet, but Sommerfeld's theory predicts the non-existent nature of the sodium doublet. This problem led to the magnetic core model that stated atomic nucleus has closed electron shells. Various experimenters, such as Alfred Landé and Paschen began working with strong magnetic fields to understand and explain the anomalous Zeeman effect. In 1921, Landé developed his g-factor and rules for spectral lines not at all associated with the anomalous Zeeman effect.

These developments concerned Bohr and his Copenhagen assistants. In 1924, Pauli, guided by Bohr, became interested in Landé's work on the anomalous Zeeman effect. Pauli's work did not explain all the lines, but he worked out the Paschen-Back effect. This work allowed him to reject Sommerfeld's magnetic core hypothesis and explain the splitting of lines by a two-valuedness of the electron. Pauli's conclusion was influenced by an article written for *Philosophical Magazine* by E.C. Stoner. Stoner tried to explain the X-ray spectra. The foundation of Stoner's paper lay in the previous papers of Walter Kossel in 1914 and Landé in 1922. Both men advanced the ideas of Bohr's model of the atom to include three quantum numbers to the levels of absorption. The crucial clue for Pauli involved Landé's suggestion that the number of energy levels of a given electron is equal to the number of electrons of a closed shell of that same quantum number. After working on the anomalous Zeeman effect, Pauli understood Landé's method of doubling as the two-valuedness of the electron. Pauli then introduced the final and fourth quantum number to create a complete system. This new understanding of a closed electron shell and its energies was published under the Exclusion Principle. His principle stated,

There can never be two or more equivalent electrons in an atom for which

in strong fields the values of all quantum numbers are the same. If an electron is present in the atom for which these numbers have definite values, this state is occupied.²⁷

Later in 1925, Pauli and others interpreted his principle in physical terms as the spin of the electron in orbit around the nucleus.

On the eve of the quantum revolution there were three significant groups developing quantum theory: München, led by Arnold Sommerfeld; Göttingen, guided by Max Born; and Copenhagen, the institute of Niels Bohr. The München School attacked the problem through a phenomenological approach, explaining observation through a mathematical model. Born's group tried to create a full-bodied system that explained natural process through strict mathematical formalism. Bohr's institute acted on many levels, bringing all the attempts together under one structure. Not only did Bohr guide and direct the others, his school concerned itself with the overall philosophical implications of quantum theory and its physical interpretation.

Niels Bohr's "...lectures provided a crucial stimulus to the further development of atomic physics," wrote Werner Heisenberg.²⁸ His quote comes after reflection on the Bohr festival, that he and others like him studying advanced physics, went to in the early 1920s. All groups began to work on the Sommerfeld-Bohr equations for quantization. The focus changed from simple structures like hydrogen to more complicated electron arrays like helium. The group's success depended on creating rules that addressed all elemental electron configurations.

²⁷ Pauli, "On the Connexion between the Completion of Electron Groups in an Atom with the Complex Structure of Spectra," in *The Old Quantum Theory*, ed. D. ter Haar, (Pergamon Press, 1967), 196.

²⁸ Werner Heisenberg, *Encounters with Einstein and Other Essays on People, Places, and Particles*, (Princeton University Press, 1983), 40.

Göttingen – Copenhagen Connection

The change in technique using astronomical perturbation theory led to advances in understanding the complicated mathematics.²⁹ The reliance on each other for motivation and collaboration among the group's members became intense. Heisenberg remembers that further stimulus by H. A. Kramers and Rudolf Ladenburg's work on dispersion theory that helped others see the use of differential equations, and work by Einstein and Bose on transition probabilities. The Göttingen and Copenhagen members started working with coupling mathematical tools and Fourier components of differential equations with energy transition probabilities.³⁰ Born, in his work on quantum mechanics, provided the scientific community with two ideas. The first used the word quantum for the first time and introduced the idea that for science to understand atomic phenomena, the tool would not involve classical mechanics. From this starting point, Born instructed Heisenberg to work on difference equations for understanding changes in electron energy states, utilizing the work by Bose-Einstein³¹ and Kramers- Ladenburg. The work became intense and everyone put forth such considerable effort and focus that nearly all awareness of the outside world collapsed. Heisenberg related a story about the group and its utter obliviousness to others outside their effort and concern.

²⁹ The astronomical perturbation theory used the complicated mathematical-physics of Hamilton-Jacobi mechanics.

³⁰ Heisenberg, *Encounters with Einstein*, 40-3.

³¹ Bose-Einstein Statistics: The formula is a statistical distribution describing the quantum behavior of particles at varied energy levels given by $f(E) = 1/Ae^{E/kT} - 1$, where A represents the photon energy state and the exponential value is a relationship between energy and temperature. The appropriate statistics are determined on the symmetry of the wave function of Schrödinger's wave equation. The Bose-Einstein statistics describes symmetrical relationships and the later formula by Fermi-Dirac explains asymmetrical properties. The later is termed bosons and the former fermions (Thewlis, *Encyclopedic Dictionary of Physics Vol. 1*, 480).

We used at that time to take our modest midday meal at a private dining-place across from the college building. One day, to my astonishment, I was summoned by our hostess after the meal to a privy conference in her room. She explained to me that, alas, we physicists could no longer eat there in the future, since the everlasting shop-talk at our table was so unbearable to those at the other tables, that she would lose her remaining customers if she continued to entertain us.³²

In the winter term of 1924-25, Born left for America, as a visiting lecturer, and Bohr's physics institute in Copenhagen acquired Heisenberg's for a short period to further quantum research. Bohr's insight influenced him to place Heisenberg with one of his talented and trusted assistants, Kramers. Kramers began to discuss with Heisenberg the dispersion formula he had worked out with Ladenburg. This collaboration advanced the idea that Arthur Compton had discovered years before with the scattering angle of light versus the incident angle of light. Kramers and Heisenberg studied the frequency change of these two different sources of light. From this, they analyzed the quantum amplitudes of emission and absorption of spectral lines. The new approach led Kramers and Heisenberg to focus on the change in energy states using transition probabilities of Bose-Einstein and to sum the products of amplitude shifts. This change in methodology was revolutionary since it set the numerical foundation for Heisenberg's later work on matrix mechanics. By the summer semester, Heisenberg returned to work with Born in Göttingen. Born suggested that Heisenberg try to advance his collaboration with Kramers, to figure out the correct quantum amplitudes for the simple case of hydrogen in relation to the classical theory utilizing products of Fourier series.³³

³² Heisenberg, *Encounters with Einstein*, 43-4.

³³ Werner Heisenberg, "Development of concepts in the history of quantum theory." *American Journal of Physics*, Vol. 43 no. 5 (1975): 126 and Heisenberg, *Encounters with Einstein*, p. 44.

Heisenberg's work dramatically changed how the quantum community viewed atomic actions. His method and direction in constructing the matrix calculus was neither direct nor his alone. In the preface to Heisenberg's quantum paper, he acknowledged those who directed and worked with him, and recognized those of the past who advanced atomic theory. He stated, "One can regard the [Bohr's] frequency condition and the dispersion formula of Kramers, together with its extension in recent papers, as the most important first steps toward quantum-theoretical mechanics."³⁴ Using past work on transition probabilities and the dispersion formula, focus on the stationary state of the electron's energy waned. Rather, the change in energy states became the focal point. Heisenberg's famous work on quantum mechanics had been already constructed with the work with Kramers. The summations of amplitude products were almost in matrix form.³⁵ In addition, Heisenberg sought help from Wolfgang Pauli, and later Born and Pascual Jordan, to help him construct a sound, formal theory. He recognized in his work that additional help was needed for the next steps of constructing the theory. The Göttingen group had the breadth of talent to help Heisenberg attain the goal he set for himself.

³⁴ Cassidy, *Uncertainty*, 180.

³⁵ Heisenberg, "Development of concepts in the history of quantum theory," 126. Dispersion formula describes nuclear reactions using similar terms as optical dispersion formulas: absorption and scattering variables, wave-lengths of incident light, a statistical factor (spin) of the bombarded nucleus, atomic resonance and energy values, Planck's constant, and parameters of disintegration of electron emission (Thewlis, *Encyclopedic Dictionary of Physics Vol. 2*, 463-5).

Constructing a New TheoryThe Matrix Calculus

The matrix revolution began with Heisenberg requesting a leave of absence from Born to convalesce on the island of Heligoland. Heisenberg suffered from hay fever because it was June, and the farmers were cutting their fields and his condition worsened.³⁶ He left to escape his suffering and during his vacation, Heisenberg approached the case of hydrogen differently by replacing Fourier expansions of the orbital amplitude with corresponding variables in tables of multiplication of amplitudes, soon to be known as matrix constructions. Heisenberg radically reinterpreted the Fourier expansions but drew heavily on Kramers' previous work on dispersion theory, as well as working within the parameters he and Kramers had established with their own work on dispersion.³⁷

Heisenberg later reflected on his work with Kramer, "...I must confess I did not know what a matrix was and did not know the rules of matrix multiplication...and later it turned out that it was matrix multiplication, well known to mathematicians."³⁸ Heisenberg reflected that Kramers' work on dispersion "hit on a very important point" physically." Though proud of his own Nobel award, he was disappointed that Kramers "never had gotten the Nobel Prize." Because Kramers' "actual amount of contribution was very large" and Kramers was the reason Heisenberg began to see things so clearly.³⁹

³⁶ Heisenberg, *Encounters with Einstein*, 45.

³⁷ Heisenberg, *Encounters with Einstein*, 45; Cassidy, *Uncertainty*, 197-203 and AHQP Paper Documents, Werner Heisenberg file 19: 3.

³⁸ Heisenberg, "Development of concepts in the history of quantum theory," 127.

³⁹ AHQP Paper Documents, Werner Heisenberg file 21: 13.

Finally, a theory, quantum mechanics, began to explain atomic phenomena. The scientific community had two goals to accomplish: to understand the physical properties of this new mechanics and secondly, to formalize matrix multiplication within a rigid mathematical system. Over the next few years, all quantum groups and their skilled participants relied heavily on each other's skills and understanding of the situation to advance quantum theory. This reliance played itself out in cooperation, collaboration, and antagonisms. A new quantum player would emerge and challenge the course of Heisenberg's quantum mechanics. That challenge only motivated the larger group to modify its underlying assumptions. A valid theory of quantum physics did materialize from this interplay of groups.

The Mystifying Properties of Matrices

The essential difficulty lay in that Heisenberg did not recognize his list of positions as a matrix nor algebraic properties of matrices.⁴⁰ In his attempt to lay the new foundations of quantum mechanics, he sought a solution to the problem of an anharmonic oscillator of the form $d^2x/d^2t + \omega^2x + \lambda x^2 = 0$. Heisenberg's result involved a "doubly-infinite" set of solutions to explain the transition between stationary electron states. The solution set was replaced by X_{mn} ($m, n = 1, 2, 3, \dots, \infty$) thus modifying the same solution set,

⁴⁰ The properties of matrices (addition, multiplication, etc.) are not the same with rational numbers. The unique construction of matrix elements do not satisfy the communicative rule of multiplication (i.e.: $2 * 3 = 3 * 2$).

$$\begin{array}{cccccc}
 & X_{11} & X_{12} & X_{13} & \dots & X_{1n} \\
 X_{mn} = & X_{21} & X_{22} & X_{23} & \dots & X_{2n} \\
 & X_{31} & X_{31} & X_{31} & \dots & X_{3n} \\
 & \dots & \dots & \dots & \dots & \dots \\
 & X_{m1} & X_{m2} & X_{m3} & \dots & X_{mn}.
 \end{array}$$

Heisenberg generalized the solution with a summation series of both x , y coordinates in the form $\langle xy \rangle_{mn} = \sum x_{mr} y_{rn}$. Heisenberg realized he had worked out a potential quantum mechanics, but then after he examined $\langle yx \rangle_{mn}$, he began to have serious doubts. His doubts aroused from the fact that $\langle xy \rangle_{mn} \neq \langle yx \rangle_{mn}$. The problem for Heisenberg was that his two cases, by the commutative rule of multiplication, should equal each other and they did not. For Heisenberg a series of mistakes brought an invalid case, but the overall hypothesis seemed to be valid.⁴¹

In July, Heisenberg returned to Göttingen and showed his work to Born. Born reviewed his manuscript before it was sent for publication to *Zeitschrift für Physik*. With the assistance of Pascual Jordan, an adept mathematician, they both recognized Heisenberg's solution set as elements of a matrix and the equality problem of his summations as the non-commutative property of matrix multiplication.

Born granted Heisenberg a request for leave of absence to give a series of lectures at Cambridge. The unforeseen advantage to Born's permission lay in the audience of

⁴¹ Cassidy, *Uncertainty*, 198-203.

those who attended Heisenberg's lectures. The lectures inspired and motivated the firm mathematical framework of P.A.M. Dirac.⁴²

Born and Jordan completed the mathematical formalization of matrix mechanics by examining the mathematical consequences of Heisenberg's work. Born and Jordan made key contributions to Heisenberg's matrix mechanics. They showed that the diagonal elements of the matrix were equal to the constant $\hbar/2\pi i$. The scheme quantified the sub-atomic world with the equation $pq - qp = \hbar/2\pi i$. They also showed that this relation equaled the Bohr-Sommerfeld conditions of quantization. They submitted their work to *Zeitschrift für Physik* and waited for Heisenberg's return to complete the formalization of matrix mechanics. The collaboration between the three-man paper was key in completing this new method of understanding atomic phenomena. The question still remained among the Göttingen group whether their mathematical concept of matrices captured the actual state of an atom and was this theory valid.⁴³

In November 1925, the Göttingen community received good news when Cambridge mathematician, Dirac, independently constructed the results of matrix mechanics, as Born and Jordan had done using a mathematical tool other than matrices (algebra) but nonetheless, the results were mathematically equivalent.⁴⁴ Dirac published his results in *Proceedings of the Royal Society*. Of his accomplishment, Dirac gave the inspirational credit to Heisenberg's Cambridge lectures on matrix mechanics. "I suppose

⁴² Thewl Thewlis, *Encyclopedic Dictionary of Physics Vol. 4*, 516-20; Heisenberg, *Encounters with Einstein*, 46 and AHQP Paper Documents, P.A.M. Dirac file: 6 and 32.

⁴³ Thewlis, *Encyclopedic Dictionary of Physics Vol. 4*, 519-20; Heisenberg, "Development of concepts in the history of quantum theory," 127; Heisenberg, *Encounters with Einstein*, 46 and AHQP Paper Documents, Max Born file 4: 8.

⁴⁴ Heisenberg, "Development of concepts in the history of quantum theory," 127 and Cassidy, *Uncertainty*, 206, and P.A.M Dirac, "The Fundamental Equations of Quantum Mechanics," *Proceedings of the Royal Society of London*, Vol. 109, no. 752 (1925): 642-53.

that Dirac's paper on transformation theory goes back to my first reading of Heisenberg's paper [matrix mechanics]."⁴⁵ The news of equivalence placed their quantum ideas on solid ground within the physics and mathematics communities. Though difficult to understand the logic of his proof, equivalence was all the community demanded of a sound theory withstanding experimental verification. All that was left for the trio to do was to write up a comprehensive paper working out existing difficulties and to explain quantum mechanics to the larger sphere outside the Göttingen and Copenhagen groups.⁴⁶

The Birth of Quantum Mechanics

The trio published their work and it became known as the three-man paper.⁴⁷ They relied heavily on each other's specialized skills to prepare this monumental paper on quantum mechanics. Each of them wrote a component of the paper, coming together at the end to edit and critically examine each other's work. Ultimately, success rested on their cooperation. They understood the critical need for each to write on their own specialized topics; this fact underlies the use of the term "three-man" paper in a collaborative effort. Born worked on collision processes, Jordan on a transformation theory, and Heisenberg endeavored to calculate the spectrum of helium.⁴⁸ Their essential work placed the new mechanics on solid ground. Still, there were questions about the physical interpretations of their theory. Their effort to make sense of this theory included others outside of their three-man group. The groups made numerous advances toward

⁴⁵ AHQP Paper Documents, P.A.M. Dirac File 29: 32.

⁴⁶ Ibid.

⁴⁷ On November 26, 1925 "*Drei-Männer Arbeit*" was published in *Zeitschrift für Physik*.

⁴⁸ Cassidy, *Uncertainty*, 207 and Heisenberg, *Encounters with Einstein*, 51.

understanding these atomic motion. Encouraged and challenged by Schrödinger's own theory only increased their drive towards a complete understanding.

Irwin Schrödinger, simultaneously with the Copenhagen and Göttingen groups, explained electron phenomena in a real experimental sense, treating the situation as a wave and examining it using partial differential equations to model the path of the electron. His approach was known as wave mechanics and was a rival theory to Heisenberg's matrix mechanics. Scientists understood Schrödinger's approach; they were familiar with differential equations and eigenvalues, but Heisenberg's model used complex, abstract mathematics to explain natural phenomena. Eventually, even Heisenberg himself realized that "to calculate shift levels in helium atom I needed... Schrödinger's theory. To do that from matrix mechanics alone would have been extremely difficult."⁴⁹ The past theories of Einstein, Bose and de Broglie heavily influenced Schrödinger's approach. The conceptual development of wave theory, similar with Heisenberg, was dependent upon peers and past key advancements in physics.

A Rival Theory: Wave Mechanics

Schrödinger wrote four successive papers in *Annalen der Physik* explaining his version of quantum theory. The beginning of his work centered on, and was inspired by, earlier effort on gas theory by Einstein. In his labor, Einstein drew on previous derivations by Bose and de Broglie. Bose gave a consistent argument tying Planck's law with Einstein's light-quantum hypothesis. De Broglie's Ph.D dissertation examined the relationship between a particle and wavelength. Combining these two ideas, Einstein

⁴⁹ AHQP Paper Documents, Werner Heisenberg File 2: 24.

argued that the idea of wave-particle duality of light could be extended to electrons.

Einstein's work inspired Schrödinger to rethink how to describe a bundle of electrons on a wave.⁵⁰

Unaware of current quantum development by Born-Dirac-Heisenberg-Jordan, Schrödinger began to develop a model of hydrogen's Balmer series constructing an equation using eigenvalues from a vibrating system model. In 1925, his differential equation computations worked. On January 26, 1926, he began to write his four-part paper on wave mechanics. Schrödinger's model simplified a three-dimensional standing wave problem in a vibrating system by including all variables of an electron's path. The exponential function took the form $\Delta\psi + 2m/K^2 (E + e^2/r)\psi = 0$.⁵¹ The wave function calculated electron energy levels and the Blamer formula for the hydrogen atom.

Schrödinger's second paper struck the Göttingen group hard by showing equivalence, through mathematical proof, of his wave function and Göttingen's matrix mechanics. With equivalence, the matrix-wave debate began between the Heisenberg and Schrödinger camps. Ending in May of that same year, Schrödinger wrote his third piece explaining his wave mechanics in relation to the Stark effect and ended the last paper by treating successfully dispersion theory, perpetuation theory, and other topics relating to atomic systems.⁵² The success of Schrödinger's theory placed the Göttingen group in an awkward position. They had an opportunity to either defend their current theory or aggressively modify the existing theory to compete with Schrödinger's

⁵⁰ Cassidy, *Uncertainty*, 210-2.

⁵¹ The equation involves multiple variables: m – mass of the electron; e – electron charge; r – electron's orbital radius for a Hydrogen atom; E – electron's energy; K – constant of the relation of Planck's constant and π ; and Δ - represents the change in the gradient of the wave function (Thewlis, *Encyclopedic Dictionary of Physics Vol. 7*, 719-208).

⁵² Cassidy, *Uncertainty*, 213-6.

presentation and interpretation of atomic phenomena. The group chose the later by undergoing significant change and modification in response to Schrödinger's initial success within the physics community.⁵³

To show the affection other scientists had for Schrödinger's ideas, Sommerfeld invited Schrödinger to give a series of talks in Munich. Sommerfeld believed that matrix mechanics was a solid theory, but "its handling is extremely intricate and frighteningly abstract. Schrödinger has now come to our rescue."⁵⁴ Heisenberg undoubtedly was upset but not for Sommerfeld's seeming defection. Heisenberg was dismayed at Schrödinger's interpretation of his wave function. Schrödinger believed that his wave function represented real three-dimensional electron waves. He wanted matrix theory and its discontinuous jumps eliminated from the debate. He wanted to keep all implications of classical physics with his new theory and with his interpretation. Unfortunately, Schrödinger had problems showing mathematically that his wave function, Ψ^2 , was a three-dimensional wave. Schrödinger's wave interpretation took a serious hit in the coming year by mathematician, Max Born.⁵⁵ Born struggled to raise his collaborator's theory to the forefront by modifying the existing theories.

Inconsistencies and Contradictions in the New Quantum Theory

In 1926, facilitated discussions by Niels Bohr with Schrödinger and Heisenberg intensely worked out problems with the two competing explanations for an electron's

⁵³ Mara Beller, "Matrix Theory before Schrödinger: Philosophy, Problems, Consequences." *Isis* Vol. 74, no. 4 (1983): 470.

⁵⁴ Cassidy, *Uncertainty*, 212-3.

⁵⁵ Heisenberg, *Encounters with Einstein*, 50-1.

path. Many heated debates between camps resulted in injured egos. A final consensus by one group claimed that wave mechanics could not satisfy the early mathematical formalism of Planck's Law.⁵⁶ The group agreed that eigenvalues of Schrödinger's differential equations did not reflect the reality of the jumps between energy states. However, no other explanation of the jumps could at the same time explain the mystifying state of an electron's path through a gas chamber.⁵⁷ These problems inherent to quantum theory plagued all groups.

Six attempts by the quantum communities tried to classify these atomic phenomena and resolve them in terms of a physical interpretation, with the aid of an international cast of physicists working in collaborative groups. Quantum mechanics involved a complex, matrix of elements not intuitively understood by explaining nature. Wave mechanics had its difficulties by not representing the jump experimental data of changes in energy states. The methods with which both Göttingen and Copenhagen worked these problems out challenged and solidified physics for the twentieth century. Both camps made strong contributions using statistical distributions to both current quantum theories.

In 1927, the first two attempts developed both wave and matrix mechanics using a statistical interpretation of the equations to represent the physical phenomena. The work by Born in wave mechanics and Dirac and Jordan in matrix mechanics set the problems against new questions that furthered the completion of the new physics of the quantum

⁵⁶ One interpretation of the wave and electron had electrons as spread out throughout the nucleus in continuum of gas like particles.

⁵⁷ Heisenberg, "Development of concepts in the history of quantum theory," 127.

realm.⁵⁸ The motivation by the Göttingen contingent can only be understood within the context of competition and motivation between them and Schrödinger's new, successful theory.⁵⁹ After Schrödinger completed wave mechanics, he applied two methods to explain the wave function, Ψ^2 . The first method assumed that waves contain an electric-charge density and spread uniformly upon a wave. This failed because electrons are localized particles occupying a single position in space. Later, Schrödinger tried to illustrate that Ψ^2 represented a wave group. If he could show Ψ^2 was a wave group, then the first attempt at interpreting Ψ^2 might prove successful and his physical wave interpretation would triumph. Unfortunately, both his methods failed and this added to the confusion about electrons.⁶⁰

Max Born's work on Schrödinger's derivation of wave mechanics provided a crucial step for the conceptual and physical understanding of wave mechanics. He examined Schrödinger's equivalence proof between matrix and wave mechanics, Born adjusted the three dimensional Cartesian space with that of Hilbert space. The difficulties of Cartesian space was that the normal descriptors of coordinates, momentum, and time were ill-defined paths for the electron's path, but with the abstract space of Hilbert's vectors an understanding of the electron was possible through the wave function.⁶¹ The square of the wave function, Born argued, can be viewed as the statistical probability that

⁵⁸ Dirac, "On the Theory of Quantum Mechanics," 661-77.

⁵⁹ Beller, "Matrix Theory before Schrödinger," 475.

⁶⁰ Heisenberg, "Development of concepts in the history of quantum theory," 127.

⁶¹ The notion of Hilbert space, created in 1906 by mathematician Hilbert, is important to mathematics and theoretical physics. This abstract construction helps to identify the quantum states in terms of a vector, ϕ , in Hilbert space instead of normal Cartesian coordinates for position and momentum. The components of this Hilbert vector are $\phi(x)$, position, and $\phi(p)$, momentum. An important quality of Hilbert space is that the dot product of two vectors, ϕ and ψ , represents the summation of change in electron energy states by the following formula $\langle\phi|\psi\rangle = \int\phi'(x)\psi'(x) = \int\phi'(p)\psi'(p)$, and supports the assumptions of quantum theory (Thewlis, *Encyclopedic Dictionary of Physics Vol. 3*, 700).

one would find a particle at a given position. That same year, Jordan and Dirac worked on their transformation theory adding a statistical element to matrix mechanics. Both group's work began a process of change as to how physicists viewed nature at the atomic level. Their findings implied that nature could not be described in a three-dimensional, determinist way. Probability of a particle had to be examined to understand quantum phenomena.⁶²

With the third attempt, the group realized that the variables assigned in the wave equations were ill-defined since the path presented itself "not [as] an infinitely continuous thin line with well-defined positions" like a missile projectile but as "a sequence of points which were not too well-defined by the water droplets [cloud chamber experiments], and the velocities were not too well-defined either".⁶³ The questions focused on how to represent an electron's path through a cloud chamber. They asked themselves how can the momentum and position of that electron be known through wave or matrix?

The Copenhagen Interpretation

In 1927, at the prestigious fifth Solvay Council, Bohr, Born, and Heisenberg all read papers that came to be known as the Copenhagen Interpretation of quantum theory. Ernest Solvay, founder of the international conferences for Nobel Laureates and prominent physicists on progressive scientific topics. The development of quantum theory from the early twentieth century beginnings can be followed through the discussions at each council culminating with the fifth council on October 5, 1927. The

⁶² Heisenberg, *Encounters with Einstein*, 52-3.

⁶³ Heisenberg, "Development of concepts in the history of quantum theory," 128.

topic for this conference was “Electrons and Photons.”⁶⁴ The readings were the last opportunity for these players to expound on their theory’s merits and claim that the solution had been found for all the contradictions and inconsistencies of both matrix and wave mechanics. The key to understanding their process is collaboration and debate. The debates between wave and matrix techniques were fierce. The solitary geniuses that ‘created’ these theories had an internal disgust for the other’s method. Other participants found their loyalties pulled at. Matrix mechanics explained energy jumps that wave mechanics could not, but Schrödinger’s method of solving differential equations provided solutions that were much easier to obtain than computing matrix elements. Heisenberg said of Schrödinger’s theory, “I definitely wanted to keep always on the quantum mechanical side and not make any concessions to the Schrödinger side...” but he later relented that there were advantages to Schrödinger’s theory in the ease of calculations.⁶⁵ Debate and confrontation motivated the groups to finalize conceptual understanding of quantum theory. Without Bohr’s leadership and insistence understanding the physical qualities of quantum theory, coupled with the philosophical implications, developments would not have taken on the process and path it did.

The contempt between Heisenberg and Schrödinger is understandable with each other’s legacy and reputation under peer scrutiny. Bohr and other’s awareness of the inconsistencies within both competing quantum theories was the initial step. The community, including Bohr, was excited with Heisenberg’s and Schrödinger’s first breakthrough papers. Heisenberg said, “it was clear at that time...that this mathematical

⁶⁴ Emilio Segré, *From X-rays to Quarks*, 92; 100; 151; 170; 194; 274. A history, along with photographs and biographies of participant conference members can be viewed at <http://homes.stat.unipid.it/mrgi/solvay/solvphoto.html>

⁶⁵ AHQP Paper Documents, Werner Heisenberg file 25: 6.

scheme...did lead in the right direction, but Bohr was not satisfied” with the seeming contradiction an electron’s path in a gas chamber.⁶⁶ Focusing on this event, two contradictory events happened: 1) a hydrogen electron maintains an orbit, and 2) a hydrogen electron does not maintain an orbit.⁶⁷ Advancement of the group’s efforts came with Born’s, Jordan’s, and Dirac’s conceptual interpretation of the quantum event using statistical probabilities. Though Heisenberg was frustrated with the modification of his theory, he did understand that without integrating both camp’s ideas and methods, the solution still eluded them.⁶⁸

In late summer of 1926, Schrödinger visited Copenhagen on the invitation of Bohr. The purpose centered on discussing and comparing the problems both wave and matrix theory faced. The talks between Bohr and Schrödinger intensified until Schrödinger became ill and took rest at his bed. Heisenberg observed, “It was a pity to see...Bohr was absolutely merciless” in their discussions over the issue that without the idea of quantum jumps, Planck’s formula was not possible.⁶⁹ The intense discussions did not revolve around emotion, but Bohr’s insistence to have clarity of argument. This ideal of Bohr’s motivated the work of everyone to explain the persisting contradictions.

The search for answers continued with Bohr leading the group’s efforts to understand the inconsistencies of quantum theory. In March of 1927, Heisenberg wrote “On the perceptual content of quantum theoretical kinematics and mechanics” for the

⁶⁶ AHQP Paper Documents, Werner Heisenberg file 21: 7

⁶⁷ AHQP Paper Documents, Werner Heisenberg file 21: 7 and AHQP Microfilm 80: Schrödinger correspondence to Prof. Wilson, Essex England, April 16, 1952, 2-3.

⁶⁸ AHQP Paper Documents, Werner Heisenberg file 22: 1-21.

⁶⁹ AHQP Paper Documents, Werner Heisenberg file 26: 13.

journal *Zeitschrift für Physik* that elucidated his Uncertainty Principle.⁷⁰ There was real disagreement between Bohr and Heisenberg over the physical and mathematical interpretation of the Uncertainty Principle.

Bohr demanded adjustments and Heisenberg sought the criticism of his colleague Wolfgang Pauli. Their heated conversations eventually led to compromise. Bohr relented philosophically to the idea of indeterminacy and Heisenberg revisited the instrumentation of the gamma ray microscope.⁷¹

Heisenberg constructed his Uncertainty Principle,

$$\Delta p * \Delta q \geq h/2\pi$$

$$\Delta E * \Delta t \geq h/2\pi$$

to explain the difficulties the current wave and matrix theories had explaining natural atomic phenomena. Both of these relations state that the measuring of all the variables,⁷² taking into account error, can not, when multiplied, exceed the constant $h/2\pi$ (6.6×10^{-27} erg./sec.), a necessarily small number. These are conjugate pairs. One experimentally measures position and momentum together, as well as time and energy. The impact of the first relation states that if an experimenter wants 100 percent accuracy on position, then the uncertainty of momentum is infinite, and vice versa. On the other hand, if we want to know energy at a certain time, then a short interval of time for the measurement must be used. Unfortunately, the value that can be obtained will be inaccurate.

Heisenberg determined the reciprocal nature of these conjugate pairs by the Gamma ray

⁷⁰ Heisenberg throughout the AHQP archives refers to his development as the uncertainty relations but other sources have two somewhat different names, uncertainty principle or indeterminacy principle. All three refer to Heisenberg's part in the Copenhagen interpretation (Cassidy, *Uncertainty*, 226).

⁷¹ AHQP Paper Documents, Werner Heisenberg file 19: 13-4.

⁷² The four variables are p- position, q- momentum, E- energy, and t- time.

microscope thought-experiment.⁷³ The collaborative work by Heisenberg and Bohr led to drastic change in quantum theory and the classical notions of causality. However, the past work of Born and Dirac exhibit the connectedness that progressive theory has with the past. Both their work on equivalence and the relation $pq - qp = h/2\pi i$ served for the foundation of Heisenberg's breakthrough in quantum mechanics, and subsequently, the Uncertainty Principle.⁷⁴

The collaborative effort by Heisenberg and Bohr brought a more clear picture to the new Uncertainty Principle. The discussions that centered on experimental mistakes by Heisenberg, and Bohr's coming closer to the philosophical underpinnings of Heisenberg's ideas, prompted Bohr to solve the problems of resolution with the Gamma ray microscope. Using the ideas of the Compton effect and discoveries of Arthur Compton, Bohr adjusted the aperture and thus the resolving power to derive Heisenberg's

⁷³ Cassidy, *Uncertainty*, 227-34 and Charles Darwin, "The Uncertainty Principle," *Science*. Vol. 73, no. 1903 (1931): 656-7. Gamma ray Microscope (Γ -ray): Heisenberg worked out his paper on the uncertainty relations by Dirac and Jordan's derivation of the transformation equations. The next step for Heisenberg was to show experimentally that these relations were consistent with the quantum mechanical formalism by attempting to illustrate the position of an electron. To locate the electron, Heisenberg's experiment used the gamma ray (Γ -ray) microscope "thought-experiment." Since the quantum experiment did not have the requisite technical instrumentation to validate predicted theoretical outcomes, scientists used this mental technique. The "thought-experiment" logically examined all parameters that affected the experiment and followed through with consistent outcomes.

In a letter to Pauli, Heisenberg expresses frustration at Bohr's insistence that problems exist in his "thought-experiment" and things are "not quite tight." Bohr explained to Heisenberg, that the uncertainty relations did not arise from the "inconsistent recoil of the electron under bombardment by light," rather from the scattering waves of the incident light as explained by the Compton effect (AHQP Microfilm 80: Heisenberg to Pauli letter on April 4, 1927).

Bohr's correction of aperture led to the correct derivation of the uncertainty relations and his subsequent work deriving complementarity. Bohr's correction of Heisenberg's analysis required a wave interpretation of the scattered light. Working with Heisenberg's insight and equations, Bohr's observations and correction showed that the wave-particle duality of matter was involved in all experiments examining atomic phenomena (Cassidy, *Uncertainty*, 240-2). For a further example of the "thought-experiment," examine the article by Prof. Charles Darwin in *Science* (1931), "The Uncertainty Principle", pages 657-658. Here Darwin examines the wave-packet experiment to deduce the uncertainty relations. Texts and histories usually use the Gamma ray "thought-experiment" by Heisenberg to explain how he came to his conclusions on indeterminacy. It is a good alternative presentation of the "thought-experiment."

⁷⁴ Cassidy, *Uncertainty*, 202.

Uncertainty Principle. This led to the revolutionary understanding of the dual nature of matter. Bohr demonstrated that Heisenberg's problem lie with misunderstanding incident light and scattering rays within the experiment.

Complementarity seeks to understand the physical implications of the Uncertainty Principle and quantum theory. Bohr's theory revolutionized the scientific communities understanding of causality. By examining an electron, one's options are open to two possibilities, either as a particle with energy and momentum, or as a wave with a wavelength and frequency. These descriptions derive from the equations $E = h\nu$ and $p = h/\lambda$.⁷⁵ The impact for science and society falls under the changes to the traditional understating of causality. The uncertainty of quantum mechanics does not appear in classical physics because of the small value of Planck's constant h . If one's objective is complete certainty, then high accuracy with instrumentation is necessary. In a quantum experiment, this is not possible, since the error introduced by the measuring apparatus is greater than that allowed by Heisenberg's Uncertainty Principle. In classical physics, causality stipulates that if two conjugate variables, momentum and position, are known, then future determination of their values is possible. In atomic measurements, the Uncertainty Principle introduces imprecision and affects the classical notion of causality. Instead of having a specific outcome for a future event, one has a causality of a statistical nature, a range of possible events. The theory goes against all intuitive understandings of that time since "we are accustomed to take it for granted that a full knowledge of the present would enable us confidently to predict the future."⁷⁶

⁷⁵ Thewlis, *Encyclopedic Dictionary of Physics Vol. 2, 2-4.*

⁷⁶ Darwin, "The Uncertainty Principle," 660.

In 1928, Dirac expanded the historical concept of an elementary particle to include a new element, the positron. Before 1928, scientists understood the fundamental elements as the small electron and the proton both defined by their mass and charge. In developing a relativistic theory of the electron, Dirac's computations deductively discovered the positron or anti-matter.

The Final Critique

In 1935, Einstein wrote the EPR paper with two colleagues at the Institute of Advance Study in Princeton, New Jersey.⁷⁷ This paper drafted a critical response to the last decade of developments of matrix and wave mechanics. The four-page document argued what became known as the 'EPR Paradox.'⁷⁸ Einstein's elaboration brought the development of quantum mechanics full circle. Albert Einstein was the main critic of the new quantum mechanics believing that, God does not play dice with the Universe. Einstein strongly believed in the classical notion of causality and the EPR paper began its argument refuting Werner Heisenberg's Uncertainty Principle. They stated that quantum events can be as certain and objective as any macro-event. For proof, they examined the collision of two particles. They followed only one of the particles until it was far enough away from the other particle, so as not to disturb the other particle in anyway. By measuring the particle's momentum, they had the measurement of the other's by following the laws of conservation of momentum. The paradox lies in this thought-experiment knowing a value for a particle by not measuring or disturbing the said

⁷⁷ Boris Podolsky and Nathan Rosen were the other co-authors of the quantum paradox paper.

⁷⁸ Ed Regis, *Who Got Einstein's Office?* (Addison-Wesley Publishing Company, 1987), 24.

particle. These conditions violated the conditions of quantum mechanics.⁷⁹ Their argument used a mathematical tool, proof by contradiction. If one finds a contradiction inherent within a theory, then the theory is incorrect. Bohr tried to provide Einstein with the answers to his criticisms, since Einstein had many problems with the new theory. Bohr said of Einstein, "He did like"⁸⁰ what the Göttingen and Copenhagen groups had done. He boxed himself into a corner because "he simply took the view of the old-fashioned philosophy of determinism from Kant."⁸¹ These conversations did not move Einstein, but was the motivating factor, coupled with quantum theories wide professional acceptance, to work with Podolsky on the beginnings of the EPR paper.⁸²

Conclusion

At the beginning of the twentieth century, the scientific community witnessed discoveries that took physicists by surprise. The science community believed that all had been discovered regarding nature's laws. These new anomalies that beset physicists were explained by the discoveries of Planck, Einstein, Compton, and Bohr. These series of anomaly explanations began the revolution to understand atomic phenomena. These breakthroughs set the foundation that Sommerfeld, Kramers, Born, Pauli, Heisenberg, Dirac, Jordan, Schrödinger, and Bohr used to modify and motivate each other in a collaborative community to build on each other's contributions. Without the sequential steps of discovery from Bohr's Correspondence Principle, to Kramers dispersion formula, and the abstract mathematics of matrices to non-Euclidean, Hilbert space, the quantum

⁷⁹ Ibid, 30-3.

⁸⁰ AHQP Paper Documents, Niels Bohr file 30: 7.

⁸¹ Ibid.

⁸² Ibid.

theories developed by the Heisenberg's and Schrödinger's teams would not have taken place. At each crucial juncture, these physicists relied heavily upon past theoretical achievements, and the support and criticism of their unique scientific community.

Heisenberg had a unique position in the quantum revolution. Along with Schrödinger, he presented the breakthrough thought that the communities of Göttingen and Copenhagen seized upon to formalize matrix and the probabilistic wave equations. This achievement solidified Heisenberg's greatness in his own mind and the scientific world. Imagine how it felt for Heisenberg when he received the laurels from the international scientific community for his theoretical work on matrix mechanics and, later, the Nobel Prize. As a child, Werner competed with his older brother Irwin for his Father's praise and pride. This quantum achievement only congealed his feelings of invisibility. This invisibility trait allowed him to fight an attack by Aryan physicists on modern physics and involved himself with Hitler's political and military machine. Heisenberg remembered fondly his experiences with the quantum community and his own achievements. This motivated him to create a new scientific community for Germany after the war and struggle to regain the addiction of glory associated with breakthrough science.

CHAPTER THREE

HEISENBERG AND THE TURMOIL OF THE WEIMAR REPUBLIC

Introduction

Political and social discourses of everyday life, and the historical foundation of those discourses, affect the construction of individual and group ideology. This is a powerful motivating factor in mobilizing a group into action. The discourse within the Weimar Republic centered around class and the importance of occupation. Academics within the upper-middle class defined themselves as independent agents with an awareness of their historic origins and the associated ideological implications of their occupations. The scientific community had a sense of being above and beyond the temporal world, an apoliticalness of all the problems of Weimar Germany. Though these perceptions did not fall within normal "objective reality," they did affect the outcomes of "social and political perceptions...political consciousness...and political mobilization" or the lack of it.¹ This apolitical perception of the scientific class was a fiction they maintained for several decades throughout social and political problematic periods. The late 1920s and early 30s would challenge this fiction for Heisenberg and his fellow physicist who chose to remain in Germany.

¹ Thomas Childers, "The Social Language of Politics in Germany: The Sociology of Political Discourse in the Weimar Republic," *The American Historical Review*, Vol. 95, no. 2 (1990): 331-58. Further elaboration by Joan Scott "reveals entire systems of meaning or value – not only how people think about particular issues, but also how they understand the organization of their lives and the world..." By examining language and the historicity of that discourse, one might analyze the actions of any group. This analysis sheds light on a group's actions and particularly makes sense of individuals of that group (Joan Scott, "On language, gender, and working class History," *International Labor and Working-Class History*, Vol. 31 (1987): 39-45).

Physicists' fears of political engagement were based on the idea that their involvement would undercut the social authority and superiority inherent in their higher social class. This argument addresses an underlying motive that their self-image would be hurt because they were acting like any other faction in society.²

The quantum community changed the perception of the world. To understand this community of scientists, an examination of the period's social, cultural, and political structures and institutions is necessary. The change and development attributed to this group can be viewed through an analysis of the scientists' larger community. This larger community is outside their individual and group institutions but involves the cultural, academic, industrial, and political establishments. Within these contexts, an understanding of the scientists' progress and construction of science be understood. All of these factors influence individual temperament and group collective reactions to the outside world.³ Even if this were not the case, the social context was changing and they soon found themselves attracted in by a gravity they and others like them could not escape.

The individual exists within the larger social network using "multiple identities."⁴ This was true for Heisenberg and others in the German science community.

² Daniel Kelves, *The Physicists: The History of a Scientific Community in Modern America* (Harvard University Press, 1971), xxiv - xxxvi.

³ *Ibid*, xliii-iv.

⁴ Childers, "The Social Language of Politics in Germany: The Sociology of Political Discourse in the Weimar Republic," 355. A concept developed in depth by Lynn Hunt and George Sheridan in "Corporation, Association, and Language of Labor in France, 1750-1850." This analysis is useful when categorizing individuals within a society or smaller group within society. Care should be used when analyzing individuals so that agency is not taken away from individuals. To recognize the multiple personalities a person may use is not just a reaction to social factors. The individual can act as he or she sees necessary to evolve and modify in the existing environment. This analysis keeps agency alive within the individual instead of for the larger group of society. One must realize that individuals make choices to maximize their particular situation based on the social elements interfering with their daily lives.

Circumstances outside their control began to direct their everyday actions. Hitler's social and political program forced this community to abandon their apolitical nature.

Heisenberg operated at many levels of personality and political ideology. Without a viable alternative, Heisenberg chose to utilize the existing structure to protect, serve, and promote German science for himself and selflessly for the future Germany.

Societal and Political Disintegration

In 1918, a political proclamation announced the first phase of the Weimar Republic. An institution dedicated to democracy, the Weimar objective was to reconstruct the German nation after the disastrous First World War. A year later, Hugo Pruess drafted the republic's brilliant constitution, but the inner workings of power still used inherited traditions, practices and taboos of the Wilhelmian past. The inherited characteristics of the Wilhelmian era plagued the new and fledgling democracy by rewarding the privileged few. However, turmoil and crisis during its first four years beleaguered the fledgling republic. Republicans and socialists competed against each other until their conflict resulted in bloody civil war and social disorder. Political chaos led to numerous political assassinations and continuing alliances of the previous power structure between industry and aristocrats, which had created many of the problems of World War I. Additionally, chaos was generated by economic instability, high inflation, an internal governmental resistance with the Kapp Putsch, and the forced agreement to the Versailles Treaty that ended the First World War.⁵

⁵ Peter Gay, *Weimar Culture: The Outsider as Insider* (Harper & Row Publishers, 1968), 10-2; 20.

The government that Germany and the world praised in 1918 was by 1932 finished and soon replaced by National Socialism. The Weimar Republic fell owing to four factors: regional factionalism, pluralism among party members, a fractured public of middle class and students, and inherent constitutional obstacles that “handicapped” politics. All of these factors speak to the failure of the upper middle class German bourgeoisie to unify their interests and present their ideas in a generalized form to the general (lower class) public.⁶

The promise of the early twenties was great but by the period of Weimar disintegration, all hope seemed unattainable. Society was ready for a solution offered by any political party that could take control and lead the nation. In an interview for the AHQP, Fru Bohr and physicist Rosenfeld recollected Heisenberg and Weizsäcker’s attitude towards the new German nationalists: “I think he [Heisenberg] fundamentally was a German nationalist. He was sorry that Hitler was such a bandit – but he was happy to see that Hitler could lead Germany to what he thought was greatness...It was the same with Weizsäcker.”⁷

⁶ Michael H. Kater, “The Work Student: A Socio-Economic Phenomenon of Early Weimar Germany,” *Journal of Contemporary History*, Vol. 10, no. 1 (1975): 71; David Abraham, “Consisting Hegemony: The Bourgeois Crisis of Weimar Germany,” *The Journal of Modern History*, Vol. 51, no. 3 (1979): 418; and Childers, “The Social Language of Politics in Germany: The Sociology of Political Discourse in the Weimar Republic,” 352. The Weimar Republic failure to organize certain interests, including the dominant classes views, integrate the interests of the lower classes after substantially “molding” and modifying their subordinate interests to that of the upper classes, and formulating an apparent classless policy.

⁷ AHQP Paper Documents, Fru Bohr file 35: 17-8.

Weimar SocietyEffects of WWI and
the Weimar Republic

The German people were affected on many economic, political, and psychological levels by World War I. All German classes were affected and all experienced the hardships of food and energy shortages. With society's understanding of Germany's great past, the end of the war brought humiliation to a nation unaccustomed to defeat. This resulted in a psychological hardship that influenced the political and social outlook of every German. World War I had separated Germany from international culture, society, and intellectual groups. The scientific community understood how this problem affected their practice and construction of science only with the threat to modern physics. Theoretical creation is closely linked to smaller communities discussing and practicing science across trans-national boundaries. Without this crossing of borders, scientific progress is retarded.

The psychological effect of the Versailles Treaty humiliated the German public. Germans believed the treaty, which ended the First World War, used "harsh and vindictive" methods for peace.⁸ The treaty called for the return of the Alsace-Lorraine region to France and the split of East Prussia between Germany and Poland. It also deprived Germany of her world colonies, the trying of war criminals, a military occupation along the Rhine River. Moreover, Article 231 brought the full anger and vindictiveness of the allies upon the German people. The article stipulated that Germany

⁸ Gay, *Weimar Culture*, p. 14.

accept responsibility for causing the war as well as the loss and damage attributed to World War I. The intent of the allies was clear; the treaty assigned war guilt. They wanted to humiliate the German nation and their leaders. Allied negotiators sought their revenge, partially by slowing the transport trains down through battlefields and public arenas, where the French public accosted the German officials at every town. Not only were the German negotiators psychologically damaged for the treaty negotiations, but the German public was as well.⁹

The new government was unable to bring all societal members together towards a common political future. These elements, including the middle class and students, looked to radical change and a leader to solve their economic and social ills. All elements of society saw each other as creating the problems within the Weimar Republic. Not only political problems, but also increasing economic instability plagued officials. In 1923, the climax came in the form of hyperinflation affecting all classes of Weimar Germany.

Problems beset students and the institutions they attended. The students blamed the government for their predicament of reduced wages, inflation, rising living expenses and costs of education, and the lowering of state support. The student groups were members of a historical privileged class within Wilhelmian society. The social and political confusion during the Weimar years presented many students with existential questions of self, whether to survive or die. Students survived by taking full or part-time

⁹ Ibid, 14; 8; 149-50.

work, but were separated out by the rest of society as the privileged class that was destroying and ruling the new government.¹⁰

The Weimar Cultural Explosion and German Idealism

Heisenberg belonged to this privileged student class. A complex set of factors that included education, income, occupation, and family background determined one's class. During the Weimar Republic, status rested on occupation, and the main indicator of social standing. Heisenberg's self-image rested on this social observation of his position and background. This society required class standing or occupational status to be printed on birth certificates, telephone book entries, and address lists.¹¹

Heisenberg and his quantum collaborators were members of a larger scientific community, whose characteristics were borrowed from the nineteenth century. Post-World War I scientists identified much from literature that expressed German idealism.¹² Culture during the Weimar era exploded with new ideas across all social venues, including music, architecture, and literature. All of these cultural components tried to express a new optimism with the new democratic government, but borrowed heavily from Germany's romantic past of great emperors. During the twenties, Stefan George, a playwright, Ernst Kantorwicz, a historian, and Rainer Maria Rilke, a poet, were three popular and established writers. George, as a poet and a playwright, translated two past German greats, Goethe and Dante, towards an elitists program glorifying Germany's past.

¹⁰ Kater, "The Work Student: A Socio-Economic Phenomenon of Early Weimar Germany," 72-75.

¹¹ Childers, "The Social Language of Politics in Germany: The Sociology of Political Discourse in the Weimar Republic," 338-40.

¹² Paul Forman, "Weimar Culture, Causality, & Quantum Theory, 1918-1927: Adaptation by German Physicists & Mathematicians to a Hostile Intellectual Environment," *Historical Studies in the Physical Sciences*, Vol. 3 (1971): 10.

This program's objective was to renew the aristocratic monarchical sense of everyday life and to perpetuate German Idealism. Kantorwicz wrote the historical biography of thirteenth century *Hohenstaufen* emperor, Fredrick Kaiser Friedrich II. He believed that there was a quiet element in German society that "yearned" for its past, its emperors, and its heroes. Maria Rilke based his poetry on Germany's past greats such as Goethe, Schiller, and Nietzsche. His writings were a favorite among the youth movements of the twenties. Young men recited his verse on their mountain outings and reprinted the work in their youth magazines.¹³

The scientific community class membership had origins and foundations in the late nineteenth century. In the 1870s, Germany's transformation to a modern industrial state was taking place. The science community's rise to prominence paralleled this period and allowed for science to have a political, ideological, and educational function in this new "natural scientific era." The role of German science was increasing and creating, within social and political spheres, a certain prestige and "untouchable" quality for its members. In 1871, the introductory speech by Rudolph Virchow at the annual meeting of *Gesellschaft Deutscher Naturforscher und Arzte* illustrates the rise of importance of the German institution of science. Virchow told his colleagues that, "science...could contribute to its [Germany] material and to its ideal values..."¹⁴ Virchow referred to the new ideals and values of the new Second Reich.

¹³Gay, *Weimar Culture*, 47-8; 49-51; 52; 57.

¹⁴David Cahan, "The Institutional Revolution in German Physics, 1865-1914." *Historical Studies in the Physical Sciences*, Vol. 15, part 2, (1985): 39.

Heisenberg's involvement in the German Youth Movement

Heisenberg chose membership in the German youth movement because of the moral idealism it represented. He chose on several instances during the occupation of Munich, to risk his life and bring food and other necessities to his and other families behind the blockade placed by the putsch movement. The blockade served as a physical and emotional barrier from the outside world creating a sense of urgency to Weimar residents. This period during the early Weimar years created chaos and havoc for the German people. Anarchy ruled before any Weimar administrators took control of the bleak situation.¹⁵ Heisenberg felt the effects of World War I first during his gymnasium enrollment. The Bavarian Army Council requisitioned many educational buildings once war was declared. Subjects enjoyed by Heisenberg and his brother were curtailed and the physics laboratory was closed to him and his experiments. In addition, a month-long school closure resulted from lack of coal. All coal resources were sent to the front lines of Germany's war. The Heisenberg family also felt the devastating effects of the First World War. In their Bavarian town, all food products such as bread, milk, meat, and sugar were rationed. Students received ration cards to receive their daily food allotments. Heisenberg was influenced by this and never forgot the sacrifices that society asked of him. He felt an attachment to Germany because of his significant sacrifice, but would

¹⁵ Robert Jungk, *Brighter than a Thousand Suns* (Harcourt Brace, 1958), 25-6.

also not have to suffer this experience again. Germany needed strong leadership and this leadership should be modeled on the past.¹⁶

The German youth movement, to which Heisenberg dedicated his early years, connected with the ideas of Germany's romantic and heroic past. Youth leaders romanticized ideals of medieval Germany that had protested against "commercialism, fragmentation, and modernity."¹⁷ Hans Breur, a youth leader, published a songbook used among the youth groups, which included German folk songs. These songs were sung by the boys on mountainous outings. On these outings, and in their own journals, they searched for meaning from German history and found heroes such as Bismarck, Friedrich of Prussia, and Martin Luther. They believed that these heroes unified Germany by being tough and realistic. This interpretation of German history created the foundation that, during the troubled Weimar years, allowed Hitler to appear as a leader embodying past heroic qualities.¹⁸ Often, during the night, Heisenberg read to the group from the German romantic poets, such as Goethe, Hölderlin, and von Wildenbruch. The group read so often that many passages were memorized and recited by the assembly.¹⁹ A Weimar writer Meinke embodied this heroic vision, arguing that the public wanted a strong leader. The form of government did not matter, the end result did. Society abhorred the political infighting that took place during the Weimar Republic. Their disgust was motivated by cultural elements remembered of the fond Bismarck era.²⁰ The youth group to which Heisenberg belonged explained their disgust with the new social order in the

¹⁶ David Cassidy, *Uncertainty: The Life and Science of Werner Heisenberg* (W. H. Freeman & Sons, 1991), 31-3.

¹⁷ Gay, *Weimar Culture*, 78.

¹⁸ *Ibid.*, 78; 86-7.

¹⁹ Cassidy, *Uncertainty*, 81.

²⁰ Gay, *Weimar Culture*, 24.

published work, "*Der Weisse Ritter*." The transcript described the history of the youth movement and their distaste for society's "decline into lifeless mechanism, capitalistic greed, urban anonymity, and personal hypocrisy."²¹

German attitudes were based on romantic understanding of German life. During the Weimar Republic, nostalgia for the good old days was based on the political and cultural stability of the previous government, Wilhelmian Germany. Wilhelmian Germany was a dictatorship laced with all types of cruelty. However, the early unrest and anarchy of the Weimar Republic led to a fond memory of the past, though that past had its own problems of unrest, lack of legal due process, and no freedom of speech.²²

After 1918, the upper middle class's, *Bildungsbürgertum*, financial resources were in jeopardy to fund their children's university career. The rising cost of living, coupled with inflation, hit this particular class hard and made their "process of elitist self-perpetuation"²³ by enrolling in courses of higher education much harder. In November of 1922, a Breslau student wrote,

I availed myself of the opportunity of summer work. My first savings were spent on mending my clothes. From day to day, I was forced to use more due to the worsening financial situation. My earnings were 250 marks per day in August, 500 marks in September and 630 marks a day in October. Where I was staying, life was so expensive that as a result, I brought only 6,000 marks into the semester, despite the greatest possible thriftiness. Presently, I can count on an amount of 2,000 marks monthly, a

²¹ Cassidy, *Uncertainty*, 68-9.

²² Walter Laqueur, *Weimar: a Culture History, 1918-1933* (G.P. Putnam & Sons, 1974), 3-4 and Gay, *Weimar Culture*, 150. The Kapp putsch was an example of the early anarchy that plagued the government. The putsch was the first serious attempt to challenge the new government. Their goals were to restore Germany to a monarchy, thus toppling the democracy. Dr. Wolfgang Kapp, the coup leader, led the rebellion in Berlin. He took over the government and the excitement could be seen when the military would not protect the Weimar officials. The putsch government only lasted four days when the civilian workers refused to serve the new government and a general strike was called. This nationwide strike crippled all metropolitan cities and the revolutionary government quickly resigned.

²³ Kater, "The Work Student: A Socio-Economic Phenomenon of Early Weimar Germany," 86.

figure which I had never built on. I need 2,000 marks to pay my tuition fees alone.²⁴

The student's letter illustrates the hard times the student and academic endured during the Weimar Republic. Academics had to adapt to the stressful times of the twenties by living at levels of subsistence lower than most parts of German society. This created mental and physical ailments that this class of individuals did not forget later in the waning years of the democracy. During these troubled years, Heisenberg remembered family difficulties with the economic problems and food shortages. He says, "...in the year of 1918, I was for some time not in school. First of all we had absolutely nothing to eat in the family...my mother was quite in despair about how to feed us boys. So we decided that I should simply work as a laborer on a farm [Miesbach, fifty miles south of Munich]." Heisenberg worked from 6:00 A.M. to 10:00 P.M. during the harvest season. The work was hard and included chopping and sawing wood.²⁵

This caste of society attributed their greatness to the past. Their philosophy stated, "We academics...have to demonstrate the qualifications for leadership to them [society], in order that they may put their trust in us..."²⁶ This reflects the social structure and beliefs held within that structure that led to the hegemony held by the upper classes and academic class that created Germany's historical caste hierarchy.²⁷

The problems of the early republic added to the Great Depression Germany experienced as large groups of unemployed workers stood in job and food lines. The lower classes waited for governmental relief in the form of social insurance policies that

²⁴ Ibid, 86.

²⁵ AHQP Paper Documents, Werner Heisenberg file 16: 3 and Cassidy, *Uncertainty*, 35.

²⁶ Kater, "The Work Student: A Socio-Economic Phenomenon of Early Weimar Germany," 84.

²⁷ Ibid, 78-84.

the progressive Germany offered. However, wages declined, conflict at home increased the numbers of broken families, jobs disappeared, and suicide rates rose with every year of economic decline.²⁸

These societal problems and stresses affected the academic class as well. Student and academic status declined and eventually began to disappear. Students became unpopular for their elite and privileged membership in Weimar society. Heisenberg lived and worked within this hostile environment. Though the Great Depression equalized many differences among Germany's classes, students were still unpopular because the thought remained among the lower classes that students still had access to a wealth that was not available to others.²⁹

Science, as Apolitical, Forced to Change

Weimar politics aligned itself with the existing traditional social hierarchy of the late nineteenth-century.³⁰ Heisenberg, and other physicists like him, saw the political environment as disturbing, but supporting the status quo, and hence did not see the need to become a political agent in changing Weimar politics.

Nazism as a Motivating Force

Heisenberg's understanding of politics began to change with Germany's "brain drain" and the Nazis assuming key university positions after their initial 1930 Nazi

²⁸ Ibid, 89.

²⁹ Ibid, 88.

³⁰ Childers, "The Social Language of Politics in Germany: The Sociology of Political Discourse in the Weimar Republic," 346.

electoral victory. Official Nazi policy aided this process of eliminating key researchers, administrators, and professors, began with the Nuremberg Racial Laws and the Nazis Party Dismal Policy.

The Nuremberg Racial Laws began with Hitler's ascendancy to the Chancellorship of Germany. Based on ethnicity and beginning with public officials and civil servants, criterion for dismissal began with those workers who had Jewish heritage.³¹ In March of 1933, the first wave of dismissals occurred with the removal of Jewish Prussian judges. These laws had a severe affect on the scientific community. The non-Aryan clause to the 1933 law dismissed three of the four directors at German research institutes: Max Born, Richard Courant, and James Franck. The toll of the dismissal policy and racial laws discharged 1/5 of all scientists, including 1/4 of all physicists, and 1,145 of 1,684 academic scholars from institutes of higher learning and research.³²

In 1933, with the rise of Hitler's Nazism, German science experienced a brain drain. By 1939, the brain drain process was complete and the position of science, in particular theoretical physics, was poor. The numbers of German scientists that left Germany were statistically significant. Thousands of the scientists who left Germany were the leaders, promising students, and assistants in their respective fields. The talent pool of future Nobel awardees had shrunk due to poor administrative appointment, unfilled teaching positions, lack of students, and an overall reduction to university chairs

³¹ "A person with mixed descent was considered Jewish if at least three grandparents were Jewish or if two grandparents were Jewish and he or she was a practicing Jew or married to one." Later addendums and supplements discounted military service as an exemption to the Nuremberg Racial Law, as seen with Max Born (Alan Beyerchen, *Scientists under Hitler: Politics and the Physics Community in the Third Reich*, (Yale University Press, 1977), 14.).

³² Beyerchen, *Scientists under Hitler*, 11; 14-5; 43-5.

pool of future Nobel awardees had shrunk due to poor administrative appointment, unfilled teaching positions, lack of students, and an overall reduction to university chairs and professorships. Heisenberg believed that the German scientific community needed to be held together for the future of German science and superiority.³³ During 1933-45, twenty Nobel Laureates who departed Germany. A majority of them immigrated during, or just after, the rise of Hitler to power in 1933 and 1934.³⁴ The ranks of these men heralded from Göttingen, Berlin, Leipzig and Graz and included men such as Albert Einstein, Erwin Schrödinger, Otto Stern, Max Born, Hans Bethe, and Peter Debye.³⁵ In addition to the unwilling immigrants there were numerous forced dismissals of administrators, directors, and researchers from all German research and academic institutions. Innovators such as David Hilbert, Hermann Weyl, and Otto Neugebauer were asked to vacate their posts.³⁶

Understandably, Heisenberg worried about his future and how the new Nazi party might affect his profession and class status. Beginning with two ideological revolutionaries, Max Planck and Max von Laue, many prominent German scientists tried to affect and change the dismissal policy and the racial laws. Von Laue gave a speech that likened the current situation to a much bleaker history of Europe, that of Galileo and the Inquisition. Von Laue ended his speech with Galileo's quiet, yet truly revolutionary

³² Beyerchen, *Scientists under Hitler*, 11; 14-5; 43-5.

³³ Laqueur, *Weimar: a Culture History, 1918-1933*, 221-259 and A. Beyerchen, *Scientists under Hitler: Politics and the Physics Community in the Third Reich* (Yale University Press, 1977), 168.

³⁴ Beyerchen, *Scientists under Hitler*, 48.

³⁵ Max Born, of all the twenty scientists, was a decorated German war hero from the First World War. Recognized among politicians and scientists as an influential German dedicated to a national cause to resurrect Germany after the war. In addition, he held an important university chair at Göttingen. In 1933,

men of science involved themselves in politics. In a letter to Professor O'Flaherty from Göttingen, Heisenberg wrote

...I had seen Max Planck in 1933 a few days after his conversation with Hitler. I had come from Leipzig to Berlin to discuss political problems [the forced immigration and removal policy] with Max Planck. Several Jewish professors had been dismissed from Leipzig University, among these was the professor of mathematics Levi who had been [an] officer in the German army in the First World War and had received many war decorations.³⁸

Other letters of Heisenberg's illustrate how he "protested the persecution of his Jewish friends and colleagues..."³⁹ Heisenberg's disgust for the government is evident in these letters for these were Germany's great men of science. Heisenberg asked himself how so many of Germany's great physicists could be forced to leave, since they were Nobel Laureates.

These dismissals worried Heisenberg and he believed he lived in "inner exile" within the German state. His wife, Elizabeth Heisenberg, used this idea of "inner exile" for her book on her husband's choices with the Nazi government. She tried to come to terms by explaining,

The difficulty with Heisenberg was that he did not think about politics as a politician but as a natural scientist. Just as he wanted to know how nature functions and how it is constructed, he wanted to know how politics is made and according to which laws it functions...In this, his great teacher was Jacob Burckhardt, and his textbook was Burckhardt's *Weltgeschichtliche Betrachtungen*. This was the book he always reached for during dangerous and oppressive periods of the Nazi regime and war...all of this told Heisenberg that part of the events and the criminal development taking place before his very eyes, seemingly without any hope of their being interrupted, could be shifted into the objective

³⁸ James O'Flaherty, "Werner Heisenberg on the Nazi Revolution: Three Hitherto Unpublished Letters," *Journal of the History of Ideas*, Vol. 53, no. 3 (1992): 489.

³⁹ O'Flaherty, "Werner Heisenberg on the Nazi Revolution," 489.

realm.⁴⁰

Heisenberg, confident in his German past, believed this government, Nazism, did not spring from romantic, idealistic German roots. Hitler did signify a strong leader that German culture required and society desperately wanted. He struggled with his decision to stay in Germany or accept positions outside the country. A letter to Wolfgang Pauli illustrates the time he deliberated on the pros and cons to stay or not. He had friends who had immigrated but he still had colleagues and, more importantly, students who were the future of Germany that were staying behind. Heisenberg expressed himself writing, "Unfortunately my own private philosophy is far and away not so clear, but rather a mishmash of all possible moral and aesthetic calculation rules through which I myself cannot find the way."⁴¹

An unknown correspondent for the journal *Science* reported that Philipp Lenard wrote a book explaining the development of modern German science. The book, *Germany and Jewish Physics* explained that "all correct scientific results belong only to Aryans, is taken seriously as the supreme criterion in judging one or another physical theory."⁴² The report lists the problems faced within German academic institutions and journals for the lack of credible scientists available to work and publish in Germany. The three prominent journals, *Zeitschrift für Physik*, *Annalen der Physik*, and *Physikalische Zeitschrift*, illustrated the deficiency argument that before Hitler's party assumed power,

⁴⁰ Elizabeth Heisenberg, *Inner Exile: Recollections of a Life with Werner Heisenberg* (Birkhäuser, 1984), 154-5.

⁴¹ Cassidy, *Uncertainty*, 47 and O'Flaherty, "Werner Heisenberg on the Nazi Revolution: Three Hitherto Unpublished Letters," 493.

⁴² Unnamed Correspondent, "Physics in Pre-Nazi Germany," *Science*, Vo. 94, no. 2447, (1941): 488-9.

German science accounted for thirty-five percent of all published papers from German nationals. By 1939, that percentage dropped to fifteen.⁴³

Retaining and Reconstructing the German Scientific Community

Heisenberg's sense of mission was strong towards holding the German science community together and, later, towards the need to rebuild that same community after the war. The "German anti-materialistic tradition of idealism" advocated action over contemplation, "*vita activa versus vita conemplativa*," Heisenberg remembered from his youth movement days. This sense of German romanticism of past ideologies meshed perfectly with the heroic character and leadership qualities of Hitler, though many, including Heisenberg, did not like his actions. What these groups admired was the devotion towards nation espoused by the new national party.⁴⁴

Deutsche Physik was a political movement during the rise of National Socialism. The leaders were Philipp Lenard and Johannes Stark, both Nobel Prize winners in experimental physics. Stark and Lenard had strong feelings of disappointment for a failing discipline that was not keeping pace with modern theoretical physics and diminishing power among the German science policy apparatus.⁴⁵

In the 1930s, National Socialist political ideology influenced the *Deutsche Physik* movement in science. Heisenberg and others like him taught, practiced, and supported modern physics. The *Deutsche Physik* movement or practioners of Aryan physics,

⁴³ Ibid, 488-9.

⁴⁴ Kater, "The Work Student: A Socio-Economic Phenomenon of Early Weimar Germany," 80.

⁴⁵ Mark Walker, "National Socialism and German Physics," *Journal of Contemporary History*, Vol. 24, no. 1 (1989): 63-5.

attacked Heisenberg's group of modern physicists. The fierce accusations labeled physicists as traitors to the German nation and they lowered themselves to work on 'Jewish physics.' This highly organized attack on "Jewish physics" motivated change from apolitical involvement in politics to a planned, organized retaliation by Heisenberg and his supporters. The political shock experienced by Heisenberg taught him valuable lessons regarding political strategies, political connections, and efficient maneuvers to fund science.

In 1936 and 1937, Stark attacked Heisenberg for practicing Jewish physics.⁴⁶ Stark chose to publish in *Völkische Beobachter*, the National Socialist party journal and *Das Schwarze Korps*, a SS newspaper. Stark's well-timed assault placed an obstacle to Heisenberg's appointment to the Munich chair of his former mentor, Arnold Sommerfeld. Heisenberg refuted Stark's claim of the inherent disintegrating quality of modern physics. His rebuttal, "*Volischer Beobachter*," challenged the capability of Aryan physics to understand the inherent theory of nature. He insisted that theory, using mathematical modeling, placed theory over observation, especially in the quantum realm.⁴⁷

Heisenberg, motivated by loss of prestige, attack upon his theoretical studies, and his vision of German superiority in science, changed his apolitical stance of pre-war Germany. Responding to political accusation, and asserting family connections within

⁴⁶ Beyerchen, *Scientists under Hitler*, 141-3. A prominent scientist argued for Aryan physics and used the press to attack and discredit Heisenberg. The attack was motivated by Heisenberg being chosen as Arnold Sommerfeld's successor to the position of chair of theoretical physics at the University of Munich. Heisenberg and all the adherents to modern physics, relativity, and quantum physics, were described as "white Jews" in 1937 in an article in *Schwarze Korp*, the official SS weekly. The argument and tone was not academic or collegial, but aggressive and declared that these scientists should support Hitler and National Socialism (Jungk, *Brighter than a Thousand Suns*, 74.).

⁴⁷ Beyerchen, *Scientists under Hitler*, 141-3. Scientists who practiced modern physics along with Jews were considered "white Jews."

the SS, Heisenberg committed himself to an activist role in Nazi Germany.⁴⁸ Heisenberg viewed his situation for action as having few alternatives. He could immigrate to a foreign country and teach at any one of numerous academic institutions. The physics department at Columbia University was the first academic institution to offer him an academic appointment. George Pegram, the chair of the physics department tried to induce Heisenberg to emigrate when Heisenberg was visiting and lecturing at Columbia. Heisenberg at that time declined, stating “he did not want to desert the nice young physicists” entrusted to him back in Germany.⁴⁹ He added that he did not believe Hitler would remain in power and would eventually lose the war. He stressed that he needed to be in Germany after the war for the eventual chaos and catastrophe that the German people faced. Before Heisenberg left, he was asked again to stay by Fermi at Ann Harbor when visiting Samuel Goudsmit’s house. Again Heisenberg declined, citing the rebuilding effort that was ahead of him and others like him.⁵⁰

The idea of immigrating had problems. He viewed escape as contradicting the idea of German nationalism and views of the romantic past. Once an immigrant, his status as a citizen would drop to second class, affecting any chance to return to Germany after the war with respect and prestige. The social class he and his family came from blocked any chance of immigration, since for him to retain his hierarchical role, he needed to be part of an occupational class that supported his social class. Heisenberg’s father had told his son, “...if you take...[a professorship] in a different country from

⁴⁸ Heisenberg’s family connection was with the Reich SS leader, Heinrich Himmler. Werner’s mother and Heinrich’s mother knew each other and were close friends. Both mothers intervened in the complicated situation that Heisenberg found himself.

⁴⁹ Jungk, *Brighter than a Thousand Suns*, 80.

⁵⁰ *Ibid*, 80-1.

Germany, it may be difficult for you later to come back to Germany...”⁵¹ Social status and the mentality with it was as important for Heisenberg as it had been for his father and others before him. Love and dedication to Germany was much deeper or more profound than loyalty to a temporal political ideology.⁵²

Heisenberg had no loyalty to the Third Reich but for the historic Germany he grew up with and fought for during the second and third decades of the twentieth century. Scientists did not believe that Hitler’s party would survive or that their excesses leading up to the war would continue.⁵³ They had hope that an intellectual upper class would regain control of the troubled state.

The call to action for Heisenberg came with the clash of ideologies and power between Aryan and modern physics. This call to action left him no other option but to remain and follow through with his personal and community goals for theoretical physics. Heisenberg had a vision of the future well beyond the temporal government of Hitler and the Nazi party. Though hard to understand, because of Hitler’s atrocities, it is essential to comprehend the reasons German scientists stayed behind and participated in the German war effort. Each confrontation between these rival scientific/political movements inched Heisenberg and others into the role of political activists in stark contrast to the early characteristic of scientists as apolitical.

In 1938, Ludwig Prandtl, at the German Academy for Aeronautical Research, argued that Germany’s future rested with the ideas of modern physics, thus arguing against the nationalistic science of *Deutsche Physik*. Prandtl carefully chose politically

⁵¹ AHQP Paper Documents, Werner Heisenberg file 26: 18.

⁵² Ibid, 18.

⁵³ Beyerchen, *Scientists under Hitler*, 200-10.

In 1938, Ludwig Prandtl, at the German Academy for Aeronautical Research, argued that Germany's future rested with the ideas of modern physics, thus arguing against the nationalistic science of *Deutsche Physik*. Prandtl carefully chose politically acceptable words to condone the advance of modern physics. Thus Himmler, the SS chief, gave Heisenberg permission to publish a rebuttal to Stark and the *Deutsche Physik* movement. Heisenberg wrote an exposition of relativity and quantum theory in the journal *Die Zeitschrift für die gesamte Naturwissenschaft*. His response would not have been possible without the support of Prandtl and the consent of the SS leader, even though Heisenberg wrote on physics and not politics.⁵⁴

Heisenberg's response had the desired effect and he began to recover his prestige. Walther Schultze, head of the Reich University Teachers League known as the *Reichsdozentenbund*, wrote a positive evaluation of Heisenberg to the party, but because of party loss of face, Heisenberg's appointment as Sommerfeld's successor was not approved. Instead, Himmler informed Heisenberg that he would receive an appointment to the chair in Vienna and he could respond to the *Deutsche Physik* movement in the political journal of the SS.⁵⁵

The advancement of Germany's war effort and the significant challenge by the Allies forced a reinterpretation of modern physics and its contribution to armaments. The proponents of Aryan physics did not deliver the possibilities that atomic physics professed. The situation between Aryan physics and modern physics became complicated because professorships and research money became available for theoretical

⁵³ Beyerchen, *Scientists under Hitler*, 200-10.

⁵⁴ Walker, "National Socialism and German Physics," 65-7.

government. The expected return from modern physics included ideas that would support the German war effort and propagate National Socialism.⁵⁶

By 1941, Aryan physicists were forced by this change in governmental policy to retreat from any attacks on Jewish physics. In 1942, an article by Heisenberg addressed the shortcoming of experimental (Aryan) physics in their contribution to weapons research and production. He challenged his opponents to produce anything as import as modern physics had. Heisenberg wrote in the language of the times and politics. His apolitical stance had come full-circle, so he and his physics could survive. The *Deutsche Physik* movement, known as the M \ddot{u} nich debate, met and prepared a statement of compromise:

1. theoretical physics, with all its mathematical tools, was a necessary part of physics;
2. the facts drawn from experience and put together by the theory of relativity belonged to the resources of physics; however, the certainty of applying the special theory of relativity to cosmic relations was not so great that a further investigation was unnecessary;
3. the four-dimensional representation of natural processes was a useful mathematical tool, but it did not satisfy the introduction of new concepts of space and time;
4. every connection of the theory of relativity with a general relativism was rejected;
5. the quantum and wave mechanics were the only tools known at that time for a quantitative comprehension of atomic processes; a penetration beyond the formalism and its directions for interpretation to a deeper understanding of the atom was desired.⁵⁷

This compromise recognized the importance of modern physics to Germany and to its plans of conquest. The five points of compromise was quite a submission to modern physics and its theoretical implications, though modern physics renounced any credit to

⁵⁶ Ibid, 74.

⁵⁷ Ibid, 72-3.

the Jewish scientists who worked on relativity and quantum theory. The National Socialist Party could recognize the usefulness of the new physics but never the Jewish participation. However, they did celebrate the German, Heisenberg. Himmler fulfilled his promise of reestablishing Heisenberg's prestige, with an appointment as director for the Kaiser Wilhelm Institute for Physics in Berlin, coupled with a chair at the University of Berlin.⁵⁸

Realities of warfare changed the dynamics and relationships between science and government. As seen by the German and Allied efforts towards production of an atomic bomb, advances and discoveries of atomic particles gave hope and promise to the military machine. There was a compromised and collaborative relationship between National Socialism and Heisenberg's tattered scientific community. No longer did German science enjoy the extensive research talent and funds that the collaborative teams of the twenties did. The mass exodus of many Jewish and other physicists left the German community lacking talent. The need for an extensive network and machine of German science was clear to Heisenberg. He needed to rebuild the scientific community not just for the immediate future, but also for years to come. National Socialism offered a chance for rebuilding German science while Heisenberg's theoretical physics offered the state a chance at winning the war. The collaborative effort of state and science cannot be viewed as either-or, but as a continuum of self-beneficial opportunities to take action towards individual goals. These individual's actions were direct political action, but they had aspirations much different and outside the immediate goals of Hitler's war effort.

With the change in influence modern physics held with the SS, Heisenberg's

⁵⁸ Ibid, 77.

had aspirations much different and outside the immediate goals of Hitler's war effort.

With the change in influence modern physics held with the SS, Heisenberg's appointment allowed him to lecture at the Reich Research Council on applications of nuclear fission. In attendance were high-ranking party officials, including Albert Speer, the highest-ranking official. On February 26, 1942, Heisenberg's lecture left many questions about the feasibility of uranium's potential as an explosive device of immense magnitude. In recollection, Speer asked whether "nuclear weapons could be used in war?"⁵⁹ Heisenberg responded yes, but current technology presented obstacles, so weapons were more for the future and not the present conflict. He further explained that,

Before addressing the question of whether this program can be carried out in practice, it will be necessary to study more closely the various processes that can generate a neutron from Uranium...the pure isotope U-235 undoubtedly represents, then, an explosive material of unimaginable force. Granted this explosive is very hard to obtain.⁶⁰

Heisenberg's talk changed the funding mechanism to a significant extent for atomic researchers. The Nazi's identification of Heisenberg's physics with national security changed the dynamics for theoretical research. Though Heisenberg presented a technological obstacle for German acquisition of the atomic bomb, the military saw the theoretical physics practical side and this was encouraging. Physics prospered with the aid of the government. The military and the SS now saw the important impact science could make in the war effort. Heisenberg and colleagues began to receive abundant support for their research on, and construction of, atomic reactors.⁶¹ Of all Heisenberg's actions, including his self-defense of modern physics, this talk was the final step for the

⁵⁹ Ibid, 82-3.

⁶⁰ Werner Heisenberg, "A Lecture on Bomb Physics," *Physics Today*, Vol. 48 (reprint -1995): 29.

scientists of the twentieth century had with support of governmental funds and resources. Without that aid, German science would not have survived.

Heisenberg made deliberate decisions and acts that addressed any doubt about his agency in participating with the Nazis. However, there is German historical precedent to frame and validate Heisenberg's decisions and actions. Between 1880 and 1900, German physicists justified receiving governmental funds to further their own research programs. Even resources appropriated only for teaching courses were often usurped for their research programs. The actions embodied an ethos of research above everything else. These scientists identified with the nation's political goals of culture. During World War I, these individuals acted as a group when they took up arms for their fight of culture. They interpreted the battlefield and the subsequent killing of Germans as an attack on German culture. Heisenberg and his colleagues remaining in Germany were forced to use the funding sources from SS, Nazis, and German military to continue their research in atomic physics, but damned the source of money. They did it so long as it helped continue their research efforts.⁶²

An apparent contradiction appears with the apolitical nature of the scientist during the twenties. This contradiction evaporates when one examines the social and political obstacles facing science during scientist's change to political action. During the Weimar Republic, the apolitical stance of scientists was self-serving. Before Hitler's rise to power, Weimar science had reached a zenith of power and influence. This weight of authority derived itself from the special social status accorded academic scientists. This

⁶² Cahan, "The Institutional Revolution in German Physics, 1865-1914," 59 and Mark Eckert, "Propaganda in science: Sommerfeld and the Spread of Electron Theory of Metals," *Historical Studies in the Physical Sciences*, Vol. 17, part 2 (1987): 197.

special status afforded them the opportunity to use illicit funds from political officials and encourage support from the public. Both the public and the government recognized these academic communities as “value-free” and the culture celebrated this scientific ideology.⁶³ Only when that position of influence and power was threatened did the community reorganize and rethink their options for action.

Heisenberg’s Reasons to Remain in Germany

German physics received considerable monetary and political support for atomic research because of the possibilities of nuclear weapons. However, Heisenberg still had problems since most of the high caliber physicists had left Germany. In addition, the lowering enrollment of graduate students affected the future possibilities for a strong German scientific community. Other obstacles for a strong community were that German publication was dwindling and American scientists were receiving more Nobel Prizes, an award that Germany used to dominate. Germany was trailing behind the Americans and the rest of the world. Germany’s scientific future looked bleak. The potential to shape the new Germany after Hitler’s war was too much for Heisenberg’s heroic nature to leave behind. Heisenberg’s characteristics of competition, pride, and a traditional sense of German nationhood were perfect for this assignment.

Heisenberg said that his decision to stay was a moral protest. During the war, this was a common reaction of many German scientists. They felt an obligation to remain to

⁶³ David Cassidy, “Heisenberg, German Science, and the Third Reich,” *Social Research*, Vol. 59 (1992): 643-4.

preserve their tradition and the future of German science. The historic foundations of his reason to stay lies in the class formation of the scientific community and their notion of a heroic self. During the rise of science and the subsequent rise in class hierarchy, German scientists built institutions of higher education for the instruction and schooling pupils. The idea also revolved around a notion of character and personality formation. This objective was met within a cultural space that identified itself with duty, adherence to principle, and a lofty concern for the inner, spiritual or *geistig* values of life. The scientific community formed in the heart of this cultural awareness and for it to succeed, it needed to adhere to these larger social and cultural mandates. A science tradition, in which Heisenberg was a member, demanded respect for the continuation of that community. The logic told him and his colleagues that to remain was heroic and the only thing do.⁶⁴

If Heisenberg left Germany for an outside academic position, then it would be desertion. In a letter to his long time friend, colleague, and mentor, Heisenberg tells Arnold Sommerfeld that immigration was tantamount to "desertion." He continues, "you know it would be very painful for me to leave Germany...I do not want to do it unless it must be absolutely so. Nevertheless, I also have no desire to live here as a second-class citizen."⁶⁵ Heisenberg's choice between staying and leaving confused him. To leave was desertion, but to stay meant downward class mobility. His pride would not allow him to occupy a second rate position within German society.

⁶⁴ Beyerchen, *Scientists under Hitler*, 1-3.

⁶⁵ AHQP Microfilm 80: Heisenberg to Sommerfeld, April 14, 1938.

The state offered Heisenberg an opportunity to accomplish both objectives, preservation of German science and to remain part of the higher-class system, not as a second-class citizen. Research into atomic possibilities for the war offered immediate protection and a source for necessary funds. Not only was it protection for Heisenberg, but it also protected many others that eventually would be called to military service or forced to immigrate. These individuals, through actions by Heisenberg and others like him, received deferments for their future lot.⁶⁶

Heisenberg's apolitical nature changed to satisfy his immediate and long-term goals of class status, research, and heroic self-image. However, he used a selective process to involve himself in political action. One's actions, under Hitler's politics, needed to be determined in a precise way. Outright denial of a dictatorship resulted in conflict with authority, but those who pretended to collaborate with the power structure could operate with impunity. Their actions were indirect and not always obvious towards active resistance. Heisenberg chose to collaborate with the enemy. This collaboration is relative since Heisenberg never became part of the Nazi political party. His membership in the youth movement had its roots in historic romantic Germany, which Hitler tried to co-opt. Similar pledges of loyalty occurred around the globe before, during, and after World War II. On March 21, 1947, President Truman issued the loyalty order, calling for oaths and investigations of all civil servants of any officials that did not sign the oath or illustrated a tendency away from moral reliability.⁶⁷ The government and Heisenberg only served each other's immediate needs and never had any real concern for the other.

⁶⁶ Cassidy, "Heisenberg, German Science, and the Third Reich," 659.

⁶⁷ Jungk, *Brighter than a Thousand Suns*, 91; 256.

The Nazis needed powerful weapons to fight the Allies, and Heisenberg had immediate goals of continued atomic research in the hope that his long-term goals of a strong scientific community may become a reality.

The German state used Heisenberg's popularity and prominence around the world to spread their propaganda of the new German state. They granted permission for Heisenberg to travel outside of Germany to lecture at various universities. During the Third Reich, state officials became more concerned with Heisenberg's outside visits, because Heisenberg maintained a "stubbornly apolitical stance" on many issues facing Germany and the European community.⁶⁸ German officials questioned Heisenberg's dependability for spreading the Nazi propaganda. Frequently, officials declined requests for his travel outside Germany. In 1941, Heisenberg requested to attend the German Institute for Eastern Work in Warsaw, Poland. The Ministry of Education, the granting office for leave, declined Heisenberg's application, citing that he was a "politically controversial figure."⁶⁹ Once Heisenberg made the decision to stay and involve himself politically, he wrote a two-part secret report on theoretical possibilities to the German Army Ordinance Office.

The atomic reactor report solidified Heisenberg's position within the German military-state apparatus. His position, after the report, was now that of the leading authority on German atomic weapons research and the report became a guideline for all other institutions that took up the weapons charge. Heisenberg enjoyed a position of

⁶⁸ Walker, "Werner Heisenberg's Foreign Lectures," 358.

⁶⁹ Ibid, 358-61.

other institutions that took up the weapons charge. Heisenberg enjoyed a position of power and influence during the Uranium Project years.⁷⁰ His power and influence can be seen through the thousands of scientists and graduate students who received military and civil service deferments, faculty funding, and the final stop to the Aryan movement against modern physics. His actions insured the fruitful labors for Germany's future after the conclusion of the war.⁷¹

Conclusion

The political and social discourse of everyday German life, and the historical foundation of those discourses, affected the construction of Heisenberg's ideology and group identification. The occupation he practiced afforded him prestige and position within German society. He identified with the upper middle class, the privileged social caste of academics. Their ideology was a historical apoliticalness that allowed them to work as independent agents, free from any political engagement. However, with the devastating effects of World War I, the troubled democracy of the Weimar Republic, the fond remembrances of a heroic, romantic German age, and the upsurge of Hitler's Third Reich, Heisenberg and the scientific community's ideology rapidly changed to political action for his and their own survival.

⁶⁹ Ibid, 358-61.

⁷⁰ Beginning on September 29, 1939, nine nuclear scientists formed the German Uranium Society or Uranium Club. Members were Bagge, Basche, Bothe, Diebner, Flugge, Geiger, Harteck, Hoffman, and Mattauch. Four weeks later, two prominent physicists, Heisenberg and Weizsäcker, joined the larger group. These meeting's objective leaned towards the development of nuclear experiment for nuclear reactors and possibly the explosive potential of uranium. The beginnings of these meetings surrounded the issue of the degree of refinement necessary for Uranium oxide required to expand their nuclear reactor purposes (Jungk, *Brighter than a Thousand Suns*, 90.).

⁷¹ Cassidy, "Heisenberg, German Science, and the Third Reich," 660.

within society was a powerfully motivation in mobilizing each group or individual into action.

The earlier twentieth-century physicists' fears that political engagement undercut their social authority and superiority, inherent to their higher social class was moot if they did not retain their community. Heisenberg, changed by the effects of the war and the Weimar Republic, knew he had assumed multiple identities to remain part of the special class and not degenerate into a second-class citizen. It was with this motivation that he stayed in wartime Germany and did not immigrate to another university in one of many Allied countries.

The quantum community changed the world. Their unique bond and communion with one another was special. Heisenberg lived his most productive years with this group and always looked back with fondness over the group of individuals working towards a quantum theory.

Not only did Heisenberg want German science to survive the war but he also wanted a sense of the cohesiveness and great group structure he had known. Heisenberg had the opportunity as a leader of the Uranium group to recapture the collaborative effort that once existed in Western Europe. Heisenberg also had the chance to create the foundation for a future great group that he, like Sommerfeld, Born, and Bohr, could recruit, direct, and lead like the men of the past had done with him. Heisenberg's actions were motivated by the German image of the romantic and heroic historic man. A man of Germany, not of politics, he sacrificed all for the love of country and not any type of self-aggrandizing ideology. Other physicists had left Germany and held influential and productive posts outside the environment he found himself in. However, he found

himself as well as others drawn in to Hitler's state by a gravity he and others like him could not escape.

CHAPTER FOUR

SOLITARY GENIUS

Introduction

In 1932, Werner Heisenberg and Irwin Schrödinger received the Nobel Prize for their simultaneous efforts on quantum theory. Subsequent academic physics texts introduce the subject of quantum physics by attributing the discovery to these scientists, exclusively.¹ A more in-depth introduction may note the work of other physicists, such as Niels Bohr or Max Born, who contributed their own expertise to the quantum project. Rarely, however do these texts and histories identify the collaborative effort in the development of matrix and wave mechanics during the 1920s. In this chapter, I analyze the development of quantum mechanics as a collaborative network of teams of researchers brought together by gifted leaders.

Our culture celebrates the “solitary genius” working alone, diligently laboring towards a great and remarkable discovery.² Society holds these individuals up as models

¹ Raymond Serway, *Physics for Scientists and Engineers, with Modern Physics* (Saunders College Publishing, 1983), 857; 895.

² W. Bennis and P. Biederman, *Organizing Genius* (Addison-Wesley Publishing Company, 1997), 5. These authors create an argument to explain the structure behind the solitary genius. Basically, their work is a nine-structured tenet on how geniuses work. Behind the genius is a system of collaboration that is essential for any creative and unique work to occur. The nine tenets: (1) Superb members; (2) Groups and leaders create each other; (3) Strong leaders (pragmatic with an original, but attainable visions, keeps members focused, respect is a critical issue since membership is voluntary); (4) Leaders know how to find talent; (5) Cooperation; (6) They are physically and mentally removed from the world around them (the apolitical nature of the 1920's physicists); (7) Groups are optimistic, not realistic; (8) The right person has the right job; and (9) Creative collaboration is so powerful a phenomenon that it inevitably raises moral issues. The author uses collaboration as an analytical tool to evaluate the construction of science, the community of scientists, and the interplay between early twentieth century physicists making the transition from old to new quantum theories.

for everyone. We look upon their actions as something to emulate. Little mention is made of associates, mentors, or subordinates who labored side by side with these geniuses. Often these laborers provided insight into the theoretical problems and how those problems were solved. They modified, broadened and expanded the work of the geniuses. In addition, these associates laid the groundwork to further discoveries.³ If geniuses were to produce their unique contribution that society praises them for, then group collaboration was not only desirable, but also inevitable. The collaborative effort included all types of scientists from different countries, engineers linking ideas to practice, and criticisms and insights from associates and subordinates, which processed the volumes of mathematical computations and theoretical possibilities.

To understand the collaborative group's dynamics, one must change the perception of a hierarchy of scientists and embrace the notion of a community of associates playing a necessary and important role in the discovery process. In comprehending group formation and dynamics, one appreciates how science is created and the community is constructed. Gifted individuals make up the membership in place during breakthrough science. Competition generated within this group and others in their field of study encourages further development. There is no super-hierarchy at work, though a less pronounced hierarchy does delineate certain necessary roles within the collaborative group. A leader is necessary for gathering the talent pool, providing vision and direction for avenues of research and serving as an arbiter between conflicts within the group. In the early 1920s, leaders such as Arnold Sommerfeld, Max Born and Niels

³ This chapter's aim is not to develop the significance of past work and how contemporary scientist's work is done on the "backs of giants," but to examine the importance of key work that led to fundamental conceptual shifts in thinking. Original breakthroughs in thought rarely occur randomly, but have foundations in the previous work of other people.

Bohr independently and collectively recruited young graduate students. These leaders participated in the early development of quantum theory, building on the past collaborative efforts that the new generation of gifted individuals further developed.

Multiple leaders do not compete, but work in concert for the benefit of all groups. The concerted work is beneficial because their members have complimentary virtues. Therefore, to be efficient, the leader must allow his members to work independently or collaboratively as their work demands. This particular point is crucial in understanding the progression of quantum physics.

Analysis of the greater group and their collaborative effort to organize, synthesize, and administer theory often leads to abandonment of the individual effort. The culture of individualism in science and the larger social environment leads to a consistent and often neglected examination of the construction of science. Gifted individuals benefit from the collaborative effort. Alone, these individuals may produce little or nothing. Years may be spent in a line of inquiry that may prove valueless. Influence and contact with others in the group provide insight, redirection, or clarification towards topics in which the gifted individuals may not have expertise.⁴ The life of the community revolves around collaboration, motivation, modification, criticism, and constructing communities. The communities help build consensus among group members. These communities do not occupy a physical space or geographic location, but instead are a state of mind that connects the participants of that collaborative effort. Three academic institutions comprised the quantum communities, which are Göttingen, München, and Copenhagen. By 1927, quantum theory worked out the inconsistencies and problems it faced earlier in

⁴ W. Bennis and P. Biederman, *Organizing Genius*, 5.

the century. These locations had expanded to allow all the participants to be a part of the “Göttingen effect” without being at the geographic location. These academic localities transcend normal space to enable the creation of ideas in a collaborative manner among all the participants of these great groups.

The construction of science is a highly collaborative affair. I will demonstrate in this chapter how the development of quantum theory led by three leaders, Arnold Sommerfeld, Max Born, and Niels Bohr at München, Göttingen, and Copenhagen, respectively, owes its theoretical success to the collaborative effort of gifted individuals. The first section examines research institutes and the leaders that occupied chairs and professorships at those universities and how their role as leader allowed them to recruit talented, young individuals and guide them into collaborative enterprises. Born, as leader, with Jordan and Heisenberg show how collaborative science works best with their joint “three man” publication of quantum mechanics.

The second section examines the evolution of the research institute into a collaborative community. I examine Bohr at Copenhagen and how he brought H.A. Kramers, Wolfgang Pauli and Werner Heisenberg together. All three accomplishments led to great revelations in quantum theory because of the atmosphere and pairing of these individuals. Bohr provided a congenial environment for all of his assistant and student to work and grow. The last section involves Bohr working with Irwin Schrödinger and Heisenberg to create a collaboration among competing quantum theories, wave and quantum mechanics. Bohr recognized the brilliance of both theories and their application to the quantum phenomena. Additionally, the last part narrates contributions by

individuals not directly involved with quantum, wave or statistical mechanics, but who made significant advancements to the theories mathematical foundations.

The Research Institute

Sommerfeld at München Constructing Community

Arnold Sommerfeld, born on December 5, 1868 in Königsberg, Prussia, attended the humanistic *Altstädtisches Gymnasium* with fellow students Hermann Minkowski and Willy Wien. Initially drawn to mathematics, history, and classical languages, Sommerfeld obtained an assistantship at Göttingen where Felix Klein presented problems in mathematical physics, which drew Sommerfeld to that field of study. He became famous for the simplified method he worked out on diffraction problems for his *Habilitationsschrift*. His ingenious solution, which the famous French mathematician Henri Poincaré adopted and praised, involved the reduction of the problem to a complex integral so that an exact numerical evaluation was possible. Furthering his accomplishments using mathematics, Sommerfeld worked with partial differential equations applying boundary-value techniques to the propagation of electromagnetic waves along wires.

In 1900, this and other works helped him become a full professor. In 1909, he met Albert Einstein who introduced Sommerfeld to quantum theory. In 1911, after reading Niels Bohr's paper on the "Constitution of Atoms and Molecules," Sommerfeld worked hard to formulate a distinct atomic theory. During the 1914-15 university term, Sommerfeld formally postulated quantizing rules that agreed with the normal Zeeman

effect.⁵ The physics community largely accepted his theory in conjunction with Bohr's atomic model.

Einstein wrote, "What I especially admire about you is the way, at a stamp of your foot, a great number of talented young theorists spring up out of the ground."⁶ Einstein's quote could not be more true, for Sommerfeld acquired numerous students to study under his leadership. His doctoral candidates included Peter Debye, Alfred Landé, Wolfgang Pauli, Werner Heisenberg, Otto Laporte, and Hans Bethe. By 1915, German nationalist and physicist Johannes Stark commented on Sommerfeld's role in the scientific community as the "energetic executive secretary...of mathematicians and physicists."⁷ He guided many young and talented physicists to problems in quantum theory that ultimately proved successful. Sommerfeld died at eighty on April 26, 1951, never receiving the Nobel Prize, but endowed with many salutatory awards for his life's work in the sciences.⁸

The first and most crucial step in forming a great group is recruiting. Hence, great groups have extraordinary leaders who recognize the abilities of individuals. Sommerfeld, Born, and Bohr recruited and nurtured the development of many premiere physicists. These individuals participated in advanced seminar work and thrived in this environment. Pauli and Heisenberg both attended university under Sommerfeld's guidance and direction. Sommerfeld created an atmosphere where the students talked to

⁵ Properly referred to as the Lorentz theory of the Zeeman effect articulates that electrons traveling parallel and perpendicular to magnetic fields experience a change in frequency given by: $qH/4\pi mc$, where q is charge, m is mass, and H is the magnetic field strength (J. Thewlis, ed, Thewlis, *Encyclopedic Dictionary of Physics Vol. 7* (Pergamon Press, 1961), 856-61).

⁶ Charles Gillispie eds., *Dictionary of Scientific Biography Vol. XII* (Scribner's, 1975), 525-31.

⁷ *Ibid*, 525-31.

⁸ *Ibid*, 525-31.

each other, argued over theory and lecture, and eventually the gifted individuals were culled from other less talented university students. It was here, as Heisenberg remembers, that young physicists interested in science came, discussed, and read with each other. "Wentzel was at the desk. He was the assistant [Sommerfeld's]. Pauli was a kind of secondary assistant...and if you had a question, you could go to them and ask...So in this way, I came into discussions with Pauli."⁹ Discussions naturally flowed out of this atmosphere. Students asked each other about the latest article from the Royal Society or the recent issue of *Physikalische Zeitschrift* and occasionally the French journal, *Comptes Rendus*. News from other institutes ultimately were discussed, analyzed, interpreted, and debated as well. At Sommerfeld's weekly *Physikalische* university colloquia, students were exposed to ideas and theories that did not always agree with the ideas that they discussed from Copenhagen or the quantum theories expressed in the *Proceedings of the Royal Society*. They learned to analyze and critique.¹⁰

Sommerfeld's two great qualities, love for young people and his skills as an instructor, made him ideal to be the initial leader of this youthful group. His course structure forced these students to mature and utilize their individual gifts and potential. Often after lecture, Sommerfeld talked with his students in the hall or back in his room. Students knew that his concern was genuine. The only drawback to his teaching style was that individuals' basics were lacking, as was the case with Heisenberg. This defect in his instruction can be understood as in effect of his zeal to advance his student's talents. Max Born, in an interview now housed in the Archives for the History of Quantum

⁹ Archives for the History of Quantum Physics (AHQP) Paper Documents, Werner Heisenberg file 18: 9.

¹⁰ AHQP Paper Documents, Werner Heisenberg file 18: 4-5; 9 and file 17: 17.

Physics (AHQP), recounts the story of Heisenberg's Ph.D. examinations with Sommerfeld and Wily Wien.

Heisenberg you know worked with me in Göttingen, but he was at the same time doing a thesis in München on hydrodynamic. Then he had to go in the spring of 1926¹¹ to München to have his orals...he appeared four months [later]...I said, 'What are you doing here; I'm glad to see you.' And he said, "Oh, I am so depressed." And then he told me that he almost failed on his oral examinations because Prof. Wien had a notice that Heisenberg didn't do his experiments properly, and he had asked him all kinds of experimental questions. He came also with the questions of the resolving power of an optical instrument, and Heisenberg couldn't answer it. So Wien decided he should not let him pass at all, though he had a most brilliant thesis. But Sommerfeld fought with all his power against it, so he got his degree, but with a very low grade.¹² ...he asked me whether I would still like him to work with him after the debacle. And I said I would...¹³ This illustrates, Sommerfeld's style as leader. He often presented his gifted students with current research problems at the expense of their fundamentals. He omitted basic classes so the student could focus on more advanced topics. A benefit that students like Pauli and Heisenberg did was to obtain the doctorates in as few years as possible. Unfortunately, this rapid educational pace left gaps in Sommerfeld's student's knowledge. Gaps that professors like Wien despised but Sommerfeld assumed the student would fill those gaps.¹⁴ But Sommerfeld's love for his students flowed over into relaxation and socialization. Often, Sommerfeld would relax by hill-walking with his students in the mountains or quench his thirst at a local beer house. But in these times of socializing, Sommerfeld never forgot his main objective: to educate. In a interview, Heisenberg fondly retells a story from university life of a *hofgarten* the group frequently visited. This relocation supports the idea that Sommerfeld constantly worked to create an academic and thought-provoking atmosphere. Heisenberg remembers that the tables were small in this cafe and made of marble, so the group used to work out problems from seminar. One time, "Sommerfeld...wrote it [a complex-integral the group could not solve] down on the table. Then we

¹¹ A fault in Born's memory as Heisenberg returned in the spring of 1923 to München to complete his dissertation under Arnold Sommerfeld (Daniel Serwer, "*Unmechanischer Zwang: Pauli, Heisenberg, and the Rejection of the Mechanical Atom, 1923-1925*," *Historical Studies in the Physical Sciences*, Vol. 8, (1977): 213).

¹² Wien gave Heisenberg a grade of F and Sommerfeld gave a grade of A. With the intervening discussion, both examiners decided on an average of low pass or C-.

¹³ AHQP Paper Documents, Max Born file: 17, 18.

¹⁴ David Cassidy, *Uncertainty: The Life and Science of Werner Heisenberg* (W.H. Freeman and Company, 1992), 106-7.

had to leave the place and go to the colloquium. A few days later, it just so happened that we came back to the same table and there we found the solution of the integral written out."¹⁵

After the recruitment of the great group, leaders then needed to constantly keep members on task and progressing. Often, the personalities of the group are extreme and are not easily led, so a leader's redirection is necessary. Sommerfeld's leadership qualities did not only focus on recruiting and creating a positive and growing atmosphere for his students, but on active direction. His direction involved choosing textbooks and exposing the students to proper theoretical background material to make their current work profitable and feasible. Sommerfeld placed emphasis on the text *Atombau* that explained the Hamilton-Jacobi theory.¹⁶ He wanted his students to understand and utilize the past work of two physicists that worked out profitable equations that dealt with atomic phenomena.¹⁷

Heisenberg's first great work dealt with the anomalous Zeeman effect, introduced and assigned by Sommerfeld in his first university term. The 1896 discovery advanced atomic models to the point where Sommerfeld's and Debye's model explained the normal Zeeman effect, but the challenge was to explain the next step, the anomalous case where multiplet spectral lines split. Sommerfeld understood the capabilities of Heisenberg and his potential. The work on anomalous Zeeman effect tested Heisenberg's tenacity and skill, and he worked closely with Landé exchanging letters and ideas. The collaborative

¹⁵ AHQP Paper Documents, Werner Heisenberg file 18: 28 and file 17: 8-10; 17.

¹⁶ With Hamilton-Jacobi equation, $\Delta S = [(\partial L / \partial q') \delta q_r]_{t_1 \rightarrow t_0} + [L \Delta t]_{t_1 \rightarrow t_0}$, one can examine a dynamical object, such as an electron, along a specific path allowing for a varying time component. In classical physics, a simpler partial differential technique is Lagrange's method, but for quantum theory the varying time element in the equation is crucial to eliminate or reduce the approximation of phase shifts by the atomic structure (Thewlis, *Encyclopedic Dictionary of Physics Vol. 3*, 568-9.).

¹⁷ AHQP Paper Documents, Werner Heisenberg file 17: 5.

effort with Lande helped Heisenberg to formulate an equation explaining the magnetic splitting of doublet and triplet spectral lines and established the rules for level structure of the anomalous Zeeman effect.¹⁸

The Sommerfeld “family” focused on atomic theory as their group’s project. Ideas from all over Europe inspired them to establish their own electron theory. To his credit, Sommerfeld realized that the group’s theory must be presented to a larger audience, through lectures, publications, texts and traveling, to promote and consolidate their theory. In America in 1922, at the University of Wisconsin, Sommerfeld explained that his “greatest desire is to contribute” to the larger community of physicists around the world.¹⁹ The new project that was before many physicists, quantum theory, Sommerfeld’s team in München was already working and their ideas could “contribute to paving the way for trusting ties [among the international community]...and a necessary prerequisite for Germany’s recovery.”²⁰ His plan of distribution worked, as the world’s publications and scientific groups read and began to lecture on these ideas emanating out of Germany.²¹

Sommerfeld brought together talented young men, often referred to as brain waves due to the international curiosity they produced.²² Even with all this brilliance, Sommerfeld was clearly the leader. Acting as patriarch, he had approval power on all

¹⁸ Edward MacKinion, “Heisenberg, Models, and the Rise of Matrix Mechanics,” *Historical Studies in the Physical Sciences*, Vol. 8, (1977): 140-1 and AHQP Paper Documents, Werner Heisenberg file 24: 1.

¹⁹ Edward MacKinion, “Heisenberg, Models, and the Rise of Matrix Mechanics,” 198.

²⁰ Ibid

²¹ Michael Eckert, “Propaganda in Science: Sommerfeld and the Spread of Electron Theory of Metals,” *Historical Studies in the Physical Sciences*, Vol. 17, part 2 (1987): 222.

²² A term borrowed from Robert Jungk’s work, “Brighter than a Thousand Suns”, when he tries to explain the immense talent that Sommerfeld had gathered around him at university and the work they did during the twenties (pp. 25-6).

actions, this authority cemented the group together. In a situation where everyone works together, it becomes extremely difficult to unravel who had ownership of an idea or theory. Whether an idea could be presented to the larger scientific community or published in a journal was settled by "father" Arnold.²³ His leadership qualities as mentor and fellow physicist matured a group of young scientists that went on to make significant contributions in their academic careers. His guidance and leadership steered them towards larger communities that extended their own talents and accomplishments.

Born at Göttingen

Constructing Community

Born in Breslau, Germany on December 11, 1882, Max Born studied in his native city at *König Wilhelm's Gymnasium* for several semesters until, in 1904, he began doctoral studies at the University of Göttingen. His German academic career was spent in Berlin, Cambridge, Chicago, Frankfurt, and finally back to Göttingen where he was forced out of public service by the Nazis in 1933. The Nazis passed a ban on all Jewish civil servants that forced him to resign his Göttingen post. He left for Great Britain where he taught at Cambridge on a Stokes lectureship and the University of Edinburgh as the Tait Professor of Natural Philosophy until 1954.

Born played an integral part in the quantum revolution. He began his fascination with atomic phenomena after exposure to the famous work of Planck's constant (1900), Einstein's quanta (1905), and Bohr's hydrogen atomic model (1913). From 1912 to 1926, Born, with the help of others in his group, worked slowly to advance the initial ideas of atomic events. In 1923, Born and his young assistant, Werner Heisenberg, published

²³ AHQP Paper Documents, Werner Heisenberg file 18: 26.

work on light spectra of the helium atom. These findings confirmed that quantum conditions existing at the time did not account for the spectra produced by helium.

Born's work in producing new quantum results and his constant peculiar spirit of Göttingen propelled the young, gifted individuals forward to explain and work out the new quantum theory. As stated by Heisenberg, Born's statistical method encouraged the development of Heisenberg's work that eventually led to him receiving the Nobel Prize.²⁴ After Heisenberg prepared his quantum mechanics, Born and Jordan recognized Heisenberg's efforts as using a fairly new branch of mathematics (matrix calculus). Enthusiasm and optimism by the physics community, as well as by scholars in mathematics and chemistry greeted the subsequent three-author paper by Born, Heisenberg, and Jordan.

In 1926, the physicist Uhlenbeck told Born, "The Schrödinger theory came as a great relief, now we did not any longer have to learn the strange mathematics of matrices."²⁵ Born and Schrödinger discussed the interpretation of Schrödinger's wave mechanics, especially analyzing the wave function, $[\omega]^2$. Born interpreted this as representing the probability density for electrons. This ingenious interpretation by Born, argued by Schrödinger, led to the 1954 Nobel Prize for Born for his statistical interpretation of the wave function. The argument Schrödinger had with Born was echoed throughout the physics community on the century old question of the duality of light.²⁶ The mathematician, Born, tirelessly worked to advance the new quantum theory.

²⁴ AHQP Paper Documents, Werner Heisenberg File 15 (Biography): 6.

²⁵ Abraham Pais, *The Genius of Science: A Portrait Gallery* (Oxford University Press, 2000), 39.

²⁶ Theories and experiments had shown, using different perspectives that light illustrated properties of being a particle and a wave.

He recognized that the current advance of atomic theory depended on a previous generation's ingenious work as he states at the Nobel Banquet, The Nobel Award is "the highest honour open to a scholar, he will sense not only the deepest gratitude [and]...indebtedness to all those who gone before and beside him."²⁷

Born's importance towards the great group is his leadership role and participation in the collaboration between Werner Heisenberg, Pascual Jordan, and P.A.M. Dirac. In addition, his revolutionary statistical interpretation of Irwin Schrödinger's work and his work on wave mechanics inspired Heisenberg to develop his Uncertainty Principle. Born "wished to form a community with others", a need he expressed in the introduction to his book, *Einstein's Theory of Relativity* (1920). He understood the drive to a higher philosophical plane to bring individuals together for a greater good, to "transcend the individual," to embrace "participation in community." He maintained that this drive brought "all religions, philosophies, sciences" together for the "purpose of expanding the 'I' to the 'We'."²⁸ The "we" is essential in the creating of Born's scientific community and how they collaboratively created science.

This uncommon trait allowed him to recognize the talents of gifted individuals and their contribution to the whole. The greatness of Born, however, was in his vision for the community and eventually he brought Heisenberg closer to realizing the importance of Schrödinger's theory. Heisenberg would later say of Born's interpretation, "Born's paper was a paper definitely in the right direction because it did connect

²⁷ A speech given at the Nobel Prize banquet dinner on December 10, 1954 in Stockholm. The full text speech and lecture found at the Nobel Museum archives at www.nobel.se/index.html. Pais, *The Genius of Science*, 30-47. and Nobel Foundation, *Nobel Lectures: Including Presentation speeches and Laureates' Biographies: Physics 1942-1962* (Elsevier Publishing Company, 1964), Vol. 3, 251-68.

²⁸ As quoted in Paul Forman, "Weimar Culture, Causality, & Quantum Theory," *Historical Studies in the Physical Sciences*, Vol. 3, (1971): 47.

Schrödinger's mathematics with a correct interpretation, namely with the probability interpretation [of the physical wave]...²⁹

Three-Man Paper

Two elements can help explain Born's group collaborative success. As mentioned, he possessed a philosophical commitment to community and his mathematical background. As physicist Alfred Landé commented, "...Max Born who is really [a] trained mathematician, has much more sense for mathematical simplicity and simple form structure as he showed by giving form to Heisenberg's wild ideas."³⁰ In the early twenties, Born offered an assistantship to Heisenberg, who after his doctoral examinations moved from München to Göttingen. The energetic atmosphere produced the first collaboration between Born and Heisenberg. With Heisenberg's published work with Sommerfeld on the anomalous Zeeman effect, Born encouraged further examination of atomic events. Together they published two papers explaining the new tool developed to deal with a many-bodied atomic problem. The first paper examined the phase relationship between two electrons in helium and hydrogen. The second dealt with adapting the existing core model to calculate the energy levels in an agitated helium atom.³¹

In a letter to Wolfgang Pauli in June 1925, Heisenberg solicited criticism for his work on quantum calculations. This note illustrates Heisenberg's uncertainty with the method he was using, but does show a breakthrough has occurred in understanding

²⁹ AHQP Paper Documents, Werner Heisenberg file 22: 1-2.

³⁰ AHQP Paper Documents, Alfred Landé file 9: 14.

³¹ MacKinion, E. Vol. 8, pp. 143-4 and AHQP Paper Documents, Werner Heisenberg file 20: 21.

quantifiable results of atomic interactions. Heisenberg writes, "I would be thankful if you could write to me which arguments speak against this formula [a function of p and q , position and momentum]...the product of two Fourier series is not uniquely defined."³² Heisenberg showed these functions to his mentor. Born recognized that the product relationship between p and q , was non-communicative, a multiplication property of matrix algebra. An essential quality of a leader was recognizing specific talent in a gifted individual. Born realized that Jordan had a unique talent for creating mathematical formalism and structured proof. Born needed help in understanding the finer points of this relationship and requested the help of his assistant, Pascual Jordan. Together they created the formalism necessary to carry to an acceptable level. Born's authority allowed him to constantly redirect Jordan to simplify the structure they were creating. As Born recalls, "Jordan had an inclination to make things algebraically involved," but "I remember only that I insisted on a certain simplicity..."³³ This simplicity resulted in the commutation rule:

$$pq - qp = - (\hbar/2\pi i), \text{ where } p, q, \text{ and } i \text{ are matrices.}$$

In September 1925, Born and Jordan published their commutation rule in *Zeitschrift für Physik*. In the article, they discussed how Jordan's proof of classical motion equations can be applied to matrices, representing momentum and position. Their published work was the beginning of a formulation of Heisenberg's matrix mechanics, the discovery of

³² AHQP Microfilm 80: June 21, 1925, Werner Heisenberg to Wolfgang Pauli.

³³ AHQP Paper Documents, Max Born file 41: 17.

the commutation law, applications of harmonic and anharmonic oscillators, and the quantification rules of electromagnetic fields.³⁴

The next step in the formation of quantum theory typifies the brilliance of the "Göttingen effect" by producing breakthroughs in quantum theory that eventually led to a revolution in atomic physics. After Heisenberg mastered the mathematics involved, he, Born and Jordan wrote systematic rules governing quantum mechanics in matrix form. Though Born left the group before any publication was complete, his correspondence with Heisenberg and Jordan began the intense collaboration period between all three.³⁵ The work the three did underlines the importance of collaboration over the talented individual. Born recalls the cohesiveness of collaboration existing between the three of them that resulted in the joint paper on matrix mechanics published by *Zeitschrift für Physik* on November 16, 1925.

[In working with Jordan]...with Jordan for weeks and weeks every morning. Heisenberg was away, but when he came back we did the same. And then I went in the middle of August to Switzerland [America too] and came back...we collaborated again. First Jordan and I and then perhaps two or three weeks later Heisenberg appeared. And then it appeared that it was almost finished...When Heisenberg came it was a little hectic...Heisenberg was also very keen on it, and so we worked very hard. But in this paper we divided our competencies. I took the chapter on perturbation theory and Hilbert space. Heisenberg and Jordan did the angular momentum things; I hardly took any part in that. I checked it, but I didn't work on it. And the writing down of it we did also in parts, and then we put it together like a puzzle. And I think the style is essentially mine, for they were very young, and they weren't accustomed to writing papers.³⁶

³⁴ Edward MacKinnon, "Heisenberg, Models, and the Rise of Matrix Mechanics," *Historical Studies in the Physical Sciences*, Vol. 8 (1977): 175-86; AHQP Paper Documents, Werner Heisenberg file 20: 5 and AHQP Paper Documents, Max Born file 41: 17; 18.

³⁵ Max Born takes a leave of duty to vacation with family in Engadine, Switzerland and present a series of lectures in the United States at M.I.T.

³⁶ AHQP Paper Documents, Max Born file 41: 19.

The above quote illustrates Born's role as leader of the Göttingen contingent of physicists working on quantum theory. His leadership skills stand out with his guidance, direction, and experience. Born recruited Heisenberg from Sommerfeld at the moment he had matured to the point where he could benefit from what Born could offer. The key to Born's success with his young talent is the commitment he had for collaboration within a community of scientists.

Bohr at Copenhagen Constructing Community

Often the role of leader proves patriarchal. The leader is a father figure that all look towards for group decisions. Patriarch approval of actions and deeds cement the group together. Many times Niels Bohr expressed criticism that young Heisenberg's theories were not quite ready for publication. Though harsh for a young academic, Heisenberg relented to the wise direction of his mentor.

Born on October 7, 1885 in Copenhagen, Denmark, Niels Bohr practiced a multi-layered approach to science. He discovered many natural laws and reflected, philosophically, on those discoveries. Completing his doctoral dissertation "*Studier over metallernes elektrontheori*" in 1911, he concluded from his analysis that a new and ingenious departure was necessary to describe atomic phenomena. This departure away from classical electromagnetic theory brought a lifelong of challenges and insightful rewards in his professional life.

After finishing his elementary studies in Copenhagen, Bohr sought the mentorship of J.J. Thompson at Cambridge, England and worked in the laboratory of Ernest Rutherford, where he began constructing the foundations of his quantum theory.

Working with the nuclear model proposed by Rutherford, Bohr continued work to explain that the anomalies of atomic phenomena could be eliminated if the atomic model incorporated a relationship between atomic number and the number of electrons. His model portrayed the nucleus at the center of circular orbits of electrons. Bohr left England to take up residence and an assistantship back in Copenhagen, where he married and published his complete quantum model in the *Philosophical Magazine*.³⁷

The next decade and half was spent collecting talented physicists and working with them to explain the problems introduced by the new atomic theories. The aim of the scientific community was to explain these phenomena within the confined laws of classical physics, a view that Bohr would turn away from eventually accepting the acausality of nature for the new quantum theory. This acceptance later would pit him and Einstein against each other, philosophically, for the rest of their lives.³⁸ With this pool of collaborators, Bohr, as well as Sommerfeld in München and Max Born in Göttingen, were seen as guides to direct and inspire a completed system of quantum theory.

With the help of H.A. Kramers, Oskar Klein, Wolfgang Pauli, and Werner Heisenberg, Bohr worked tirelessly at his Institute for Theoretical Physics in Copenhagen. Between the years of 1918 and 1922, he and Kramers worked on extending his theories by analyzing line spectra. Their work resulted in a three-part publication that created the theoretical periodic system of elements for which he was awarded the Nobel Prize in

³⁷ Gillispie, *Dictionary of Scientific Biography*, 243.

³⁸ Bohr's Copenhagen School developed the quantum theory that challenged the Newtonian view of casualty. The Copenhagen Interpretation replaced causality with acausality. This development Einstein could not accept. Bohr remembers Einstein being very "difficult" and "had a lot of criticism" of our current theory even though "he was shown at every single point...that he was wrong." Einstein believed that "God does not roll dice" which fueled the debate between Bohr and himself for the rest of their lives (AHQP Paper Documents, Niels Bohr file 30: 7).

1922. From that point on, with assistance from Pauli and Heisenberg, he directed his work to formulate a complete theoretical foundation for quantum theory. Working with the anomalous Zeeman effect, Pauli was the first to advance to this goal by his Exclusion Principle a theory that led the group to one fundamental structure of the quantum world.³⁹ This advance was at variance with the previous quantum conditions, but Heisenberg solved this crisis with his mathematical formalism of matrix calculus that embodied the quantum postulates.

Bohr and Heisenberg continued to expand the new quantum theory to explain the physical side of the theory. The new theory treated matter as a wave (Schrödinger's theory) and a particle (Heisenberg's theory), but epistemological problems plagued Bohr. His philosophical side did not accept a theory that had such glaring inconsistencies. One could choose a theory to work with, but as P.A.M. Dirac showed mathematically, both theories were equivalent, so a physical analysis of this problem was necessary for Bohr. In 1933, at the Solvay Conference along with the formulation and presentation of Heisenberg's Uncertainty Principle, Bohr presented his theory of complementarity.⁴⁰

By 1939, Bohr lectured at Princeton as a visiting lecturer only to return after 1943 in a dramatic escape from Nazi-occupied Denmark. His work on nuclear theory and his close association with many German atomic physicists led him to act as an advisor for the

³⁹ Exclusion Principle states that each stationary state of an atom can only be occupied by one electron.

⁴⁰ This conjecture explains the physical implications of the uncertainty relations and quantum mechanics. The principle of complementarity states: *It is not possible to describe atomic phenomena in as complete a manner as classical ones, since the pair of conjugate variables that must be known for an exact description in the latter case are mutually exclusive in the former.* The force of this principle lies in the interpretation of experimental measurements of atomic events in terms of corresponding classical Newtonian terms. A good example concerns the particle-wave duality of light. By examining the uncertainty relations, an electron, depending on the experiment, can be seen in terms of momentum (wave) or position (particle) (Thewlis, *Encyclopedic Dictionary of Physics Vol. 2, 2-4.*).

Allied powers and the Manhattan Project during World War II. His discussions convinced the leaders of these nations that the German effort to build a nuclear bomb was real and in the advanced stages of completion.

Bohr's later years were spent strengthening his institute, Nordic science, and pondering the philosophical implications and questions regarding the work he and others accomplished in science over the first half of the twentieth century. He dedicated himself to the building of an international community of physics so that cooperation between great groups would be possible. He focused, at his banquet speech accepting the Nobel Prize, on the positive aspect of community and collaboration and how it reflects his future vision.

...I also beg leave at this banquet to propose a that toast of the international cooperation for the Advancement of Science, which is, I may say, in these so manifoldly depressing times, one of the bright spots visible in the human experience.⁴¹

Constructing the Research Institute into a Scientific Community

Bohr's brilliance infused enthusiasm for the new project in extending the old quantum theories of the past and recruiting the talent that would succeed at the endeavor of advancing the old theory. Bohr's miniscule ego allowed young brash scientists to criticize and approach him. From these encounters, Bohr had a large enough pool to select and recruit the next generation of talented and gifted physicists.

⁴¹ A speech given at the Nobel Prize banquet dinner on December 10, 1922 in Stockholm. The full text speech and lecture found at the Nobel Museum archives at www.nobel.se/index.html.

Bohr's co-authorship on the quadratic Stark effect of hydrogen inspired Max Born and his colleagues to invite him to speak. In 1922⁴², after a summer of talks in Munich,⁴³ Göttingen invited Bohr to give a series of talks on his Stark paper. All the new "brain waves" from all over Europe attended the "Bohr festival." Young Heisenberg was one of the 100 attendees that listened as Bohr explained his and Kramers' paper. After the Bohr gave his paper, Heisenberg questioned Bohr on inconsistencies within his paper.⁴⁴ Bohr's considerable calm in asking Heisenberg to discuss the difficulties of his own theory and its recurring consistency problems, sets the tone of this unique relationship and emphasized his leadership abilities in contrast to Heisenberg's temper. Through his understanding of the greater situation, Bohr recruited for his team and in the process acquired a disciple who saw Bohr as his greatest mentor. Though individuals stand out in the public's attention, cooperation among members, who exhibit unique and progressive skills is key. In 1923, Werner Heisenberg, while working with Max Born in Göttingen, worked out a new approach to the core model developed with Sommerfeld in Munich. Both Born and Sommerfeld urged caution on the new theory. Frustrated, Heisenberg sought the advice from the master of physical insight, Niels Bohr, because, "Bohr is the

⁴² This date of 1922 is cited by Robert Jungk in his work, "Brighter than a Thousand Suns," but is contradicted by an interview Heisenberg gave to Thomas Kuhn for the AHQP project. There could be discrepancies regarding earlier talks Sommerfeld took Heisenberg to, but for this argument, the crucial talk is Heisenberg's outburst of emotions and criticisms I am after. I have chosen to stick with the 1922 timeline for my purposes.

⁴³ Sommerfeld took Heisenberg to Munich to listen to the summer colloquiums. Heisenberg remarked that so many talented people attended these talks. People from Göttingen and Copenhagen were there and interested in the new topics of relativity and quantum theory. What amazed young Heisenberg was the talent in both fields of physics and mathematics with people such as Born, Hilbert, Bohr, Minkowski and Hund.

⁴⁴ Jungk, *Brighter than a Thousand Suns*, 25-30 and AHQP Paper Documents, Werner Heisenberg file 16: 13-14.

only person who, in the philosophical sense, understands something of physics.”⁴⁵

Heisenberg’s long letter to Bohr, written in Latin, tentatively explained the intricacies of his new core model. Bohr wrote back inviting Heisenberg to visit Copenhagen and work with him. This action would be the final recruitment by the three leaders of this great group. It was now up to Niels Bohr to polish the talent of young Heisenberg. Permission for the Copenhagen stay was granted by Born. Born gave Bohr permission, while Born was away in America, to work with the young Heisenberg on the condition Heisenberg would be back for the summer term.⁴⁶

Heisenberg refers to Bohr not just as a patriarch, but also as the Pope, head of all great leaders. Bohr had the connection of the past and the connection with the future generation that none of the other leaders had. Bohr, as leader, participated in the recruitment of these gifted individuals, but also encouraged these young physicists to perfect their new quanta ideas. These accomplishments of the twenties had to do with Bohr’s insistence to address all inconsistencies within quantum theory, even though tremendous breakthroughs had already been made. Though these editorial comments from Bohr frustrated the young members of the group, this quality of his character is the finer point that separates Bohr from Sommerfeld and Born, as leaders.

Niels Bohr constructed a community at Copenhagen that all throughout the scientific community wanted to be a part of. As a letter between Kramers and Dennison states, “Copenhagen is it,” if one wants to discover new cutting edge physics. Bohr’s institute is “alive” and “everyone important visits and works” in a collaborative manner

⁴⁵ Cassidy, *Uncertainty*, 171.

⁴⁶ *Ibid*, 170-1; 183.

and “the theoretical life is very there.”⁴⁷ The only other center of relevant quantum investigation was Göttingen. Copenhagen focused on philosophy and conceptualizing nature, while Göttingen focused on the mathematical formalism of quantum theory.⁴⁸ Nevertheless, both institutions were dealing with the same crisis in physics. The community of physicists at large was not giving a sufficient examination to quantum theory. In fact, Heisenberg states, “around 1918 most physicists had in some way pushed quantum theory away.”⁴⁹ Some scientists knew and accepted the ideas of Planck and Einstein, but current work, like Bohr’s and others’s, repulsed others. The procedures that Bohr was creating and teaching to deal with these new anomalies contradicted parts of classical physics. Bohr accepted these contradictions as stated in his 1922 article on the Stark effect that quantum theory still contains many contradictions, but insisted that his group solve them. Bohr and his group, however, were in the minority. Otto Stern’s comment, “Well, if that’s correct, then I give up physics...” represented the consensus of the scientific community during the early twenties.⁵⁰

Bohr fostered a unique and close relationship between his assistants and with those assistants. In a letter dated June 18, 1926, Irwin Schrödinger wrote to D. M. Dennison to inform him of his activities and the discussion problems revolving around the Copenhagen group. Though Schrödinger unaware of Dennison departure back to the

⁴⁷ AHQP microfilm 80 and AHQP Paper Documents, H.A. Kramers file 31 (letters): Kramers to Dennison June 1, 1927.

⁴⁸ AHQP Paper Documents, Werner Heisenberg file 21: 22.

⁴⁹ AHQP Paper Documents, Werner Heisenberg file 20: 4.

⁵⁰ AHQP Paper Documents, Werner Heisenberg file 20: 4; file 16: 13; and file 21: 7. Only later would physicists accept a new axiomatic system that was “thoroughly different from the old” way of classical (Newtonian) methods of investigation. This new method was logical and to a large extent free of the anomalies and contradictions the old system presented. The new quantum theory, David Hilbert the mathematician said, was so complex in explaining atomic events that “...after all, only the mathematicians can really do the thing [physics] in the end.” Extracted from the AHQP Paper Documents, Werner Heisenberg file 20: 9 and file 23: 8.

United States, asks Dennison to give [his] kindest regards to Mr. Bohr and Mr. Heisenberg.”⁵¹ There was a closeness shared among all who worked and stayed at Bohr’s institute. Though Schrödinger, Heisenberg, and Bohr had many arguments between them, Bohr kept cordiality always in their relationship.

Bohr brought together the future of atomic physics. As Heisenberg remembers, his first visits were filled with fruitful discussions. During Heisenberg’s early visits to Copenhagen, he stayed at Mrs. Maar’s boarding house not too distant from Bohr’s institute. He fondly recalls the “many conversations...of quantum development” with the other boarders.⁵² Heisenberg had many conversations with John Stuart, a doctoral candidate from Yale University and an assistant Professor at McGill University in Montreal, on the normal Stark effect and the direction quantum theory should go. These intimate talks allowed the gifted individuals to benefit from each other’s unique skills and help each other advance their own particular contribution to Bohr’s overall research program.⁵³

During Heisenberg’s first work visit in the spring 1923 and two winter terms of 1924 and 1925, Bohr urged Heisenberg to work with his assistant Kramers. Kramers’ ability helped Heisenberg to mature and develop an insight into the atomic world that later set the foundation for much of his Nobel Prize work. He introduced Heisenberg to a larger audience of ideas through journals and conferences through his understanding of

⁵¹ AHQP Microfilm 59, June 18, 1926 Irwin Schrödinger to D.M. Dennison.

⁵² AHQP Paper Documents, Werner Heisenberg file 20: 15.

⁵³ Ibid, 15.

multiple languages. Together, they worked on an atomic dispersion formula. Their combined talents and collaboration resulted in a published paper.⁵⁴

Bohr's guidance led Wolfgang Pauli and Heisenberg to cooperate towards extending the new idea of Pauli's Exclusion Principle.⁵⁵ Letters between the two and Bohr motivated the team to examine Heisenberg's core model and Pauli's Exclusion principle to further their quantum ideas. In March of 1925, their alliance began with Pauli's visit to Copenhagen. This crucial visit began to modify Heisenberg view of the new quantum core model, Bohr's radiation theory, and Pauli's work. The central importance is Heisenberg's change of mind regarding a clear picture of the physical situation and the influence Pauli and Bohr had on Heisenberg's ideas. Heisenberg later used these theory of observables and his work with Kramers to construct his famous quantum structure. Pauli's continued correspondence and intervention to influence Heisenberg was crucial in the modification of Heisenberg's methodology. Bohr understood the importance of placing Heisenberg with Pauli's mature approach using a physical interpretation to reconcile all contradictions. Heisenberg later reflected that his revolutionary vision of matrix mechanics had "its roots in the collaboration" with Pauli and Bohr.⁵⁶ The Pope had to give his blessing. Heisenberg sent both Pauli and Bohr a

⁵⁴ Serwer, "Unmechanischer Zwang," 220 and AHQP Paper Documents, Werner Heisenberg file 21: 5.

⁵⁵ The exclusion principle formalized from studying atomic spectra states: *no two identical particles in any system may occupy states which have the same set of quantum numbers*. This translates, in classical language, as no two electrons can occupy a singular orbital plane, simultaneously. Using the new quantum language, the angular momentum and atomic number are expressed using the wave function of a system. The stipulation is that the wave function must appear to be asymmetric to any other identical particles in the wave. This relationship is given by the formula: $\Psi = \varphi(x_1)\psi(x_2) - \psi(x_1)\varphi(x_2)$: where ψ and φ are wave functions and x and y represent position and spin coordinates (Thewllis, J. ed, Vol. 3, p. 8.).

⁵⁶ AHQP Paper Documents, Werner Heisenberg file 23: 6.

draft copy of his manuscript. The criticisms from both Pauli and Bohr were encouraging and addressed the inherent problems with his theory.⁵⁷

Bohr's merciless and driving commitment to consistency and clarity of argument encouraged sound theory among his students. Bohr pushed his students, but not in a subordinate relationship. Bohr had the insight as leader to connect the past and the direction of future theory. Bohr understood that a new discovery had been accomplished in quantum mechanics, but he worried that the theory needed a "mathematical scheme" as he was upset with the current framework that was being constructed.⁵⁸

Bohr had invited Heisenberg to come to Copenhagen and suggested to the young Heisenberg that "Fourier components of this motion [atomic] in some way correspond to the oscillators" and an arrangement of these oscillators are nothing more "but a matrix."⁵⁹ Heisenberg later reflected that at this point Bohr had directed the group in understanding the new theory through his paper with Kramers and Slater.⁶⁰

Choice between Two Quantum Theories

With the choice between two quantum theories, Bohr stressed the clarity issue twice, once with Schrödinger over his physical interpretation of wave mechanics and another time with Heisenberg, where he disagreed with Heisenberg's approach in constructing the Uncertainty Principle.

⁵⁷ AHQP Paper Documents, Werner Heisenberg file 23: 6 and Serwer, "Unmechanischer Zwang," 195; 217-222; 244-5.

⁵⁸ AHQP Paper Documents, Werner Heisenberg file 23: 6 and Serwer, "Unmechanischer Zwang," 219.

⁵⁹ AHQP Paper Documents, Werner Heisenberg file 19: 3.

⁶⁰ Serwer, "Unmechanischer Zwang," 219-20. The Bohr-Krammer-Slater paper charged the group to view reality differently than they had in the past. "Probability" was established "as a kind of reality" and "it was real." (AHQP Paper Documents, Werner Heisenberg file 19: 2).

Bohr's disagreement was rooted in Schrödinger's insistence "that the solution to our [physics community] difficulties in atomic physics will depend upon liberation from the rooted prejudices of absolute causality."⁶¹ In December 1929, these remarks, by Schrödinger, concluded his lecture by stressing the prejudices of the Copenhagen and Göttingen groups. Both groups, who helped to create the current quantum theories, believed that causality in the Newtonian sense was not valid in the atomic realm. This was the source of difficulty between Bohr and Schrödinger. In addition, Schrödinger's interpretation of his wave mechanics violated Bohr's physical ideas that would lead to Complimentarity.⁶² The disagreement between these two was not fierce enough that Schrödinger forsook the opinion of Bohr. On the contrary, Schrödinger sought Bohr's advice even though as Heisenberg once wrote, "It was a pity to see [Schrödinger]...after he gave this talk, and then he was criticized by Bohr [even though Schrödinger was sick in bed] and Bohr would sit at Schrödinger's bed and would say 'Now see Mr. Schrödinger, you must see, you must see!'"⁶³ This relentlessness by Bohr to confine the parameters of the argument and to seek clarity for him and the group led to continued talks for many months. These talks occurred until the Solvay conference, in Como, Italy, where the ideas and interpretations of quantum and wave mechanics were solidifying, with the exception of Einstein.

After Schrödinger's visit, heated talks between Bohr and Heisenberg erupted when Bohr demanded that Heisenberg deal with "Schrödinger's waves" and the physical implications of quantum theory. In rebuttal, Heisenberg only wanted to deal with his

⁶¹ AHQP Paper Documents, Werner Heisenberg file 22: 30.

“mechanical scheme...and use Schrödinger’s theory perhaps as a mathematical tool sometimes.”⁶⁴ Bohr was very frustrated because both theories needed to be reconciled.

It was difficult for Schrödinger and Heisenberg to agree their theoretical methods differed. Bohr pushed however until there was a realization by Schrödinger and both men to compromise and try to understand the importance and physical interpretation of wave and matrix mechanics. Schrödinger left Bohr and Heisenberg not to modify his theory. Though frustrated, their long and impassioned conversations, Bohr and Heisenberg did eventually reach an understanding of each other’s viewpoints. The collaborative compromise lies at the foundation of the Uncertainty Principle and the theory of Complementarity, also known as the Copenhagen Interpretation.⁶⁵

The end of the Bohr’s great group came with the imminent invasion of Denmark by Nazi troops. With help from sympathetic admirers, Bohr escaped in 1943, to England via Sweden where he then proceeded to America to share his ideas of Hitler’s progress with the atomic bomb. The hatred Bohr had for the Germans can be seen regarding his actions with his Nobel medal. Before the Germans arrived, Bohr took his medal and placed it in a solution of acid to melt the medallion. He hoped that one day, after his

⁶⁴ AHQP Paper Documents, Werner Heisenberg file 23: 14-6. An interesting note that cannot be left unsaid- Heisenberg’s views of only wanting to use Schrödinger’s “wave tools” and not to consider the physical (Schrödinger’s) interpretation is contradicted approximately ten years after the interview with Thomas Kuhn for the AHQP. In a letter dated July 12, 1974, Heisenberg writes Prof. Edward McKinnon, “On page 63 you express the opinion that only Bohr felt the need for an (sic) physical interpretation of quantum mechanics, while other physicists, including myself, considered the mathematical scheme as a sufficient explanation of the phenomena. I believe I have always shared the opinion of Bohr...” This seeming contradiction, I believe, does not collapse any part of the great group and collaboration argument. If it is true of the later opinion, it just shows Bohr’s influential powers of argument with one of his gifted individuals (AHQP microfilm 80: Heisenberg to McKinnon on July 12, 1974, 1-2).

⁶⁵ AHQP Paper Documents, Werner Heisenberg file 23: 4-18.

return, he could reconstruct the disfigured award. The physical and psychological separation from his German assistants was complete and the quantum group disbanded.⁶⁶

Collaboration among Gifted Individuals

Gifted individuals compromise the great group and the nature of great groups is collaboration. These individuals compete with each other to encourage and generate energy within the group. A uniting bond often exists within the group's collaboration with each other. Two consequences of the stress often emerge. The characters and personalities are difficult and strong within and outside the group. Of all the unique personalities and inter-communal conflict, Schrödinger and Heisenberg best illustrate this discord. These individuals do not work in a traditional sense of team work. They modify their behavior and sense of team to maximize the collaborative effort.

The founder of wave mechanics, Irwin Schrödinger was born in Vienna, Austria August 12, 1887. He was home-schooled by a local Vienna instructor and attended the University of Vienna at the turn of the century and enjoyed the mathematics, physics and the study of ancient languages. In 1910, Schrödinger received his doctorate and later worked at the university, supervising a physic laboratory. This task impressed upon him the importance of fine measurement and precision in experiments.

Schrödinger's academic career randomly selected numerous posts throughout the previous Austro-Hungarian Empire. He finally accepted a chair in Zurich that formerly was held by the great physicists Max von Laue and Albert Einstein. In 1924, the revolutionary publications by Frenchman Louis de Broglie, Bose, and Einstein ignited

⁶⁶ Jungk, R., p.102 and AHQP Paper Documents (biography) file on Niels Bohr.

Schrödinger's curiosity about quantum statistics and wave propagation. In 1925, in a letter to Wilhelm Wien, editor of *Annalen der Physik*, Schrödinger wrote, "I believe that I can give a vibrating system...that yields the hydrogen frequency levels as its eigenfrequencies."⁶⁷ By 1926, he established the new quantum theory of wave mechanics. Relief among the physics community spread, as Schrödinger's mechanics of differential equations simplified the then complicated approach of Heisenberg's matrix mechanics, a mathematical scheme that not all physicists were accustomed to, not even Heisenberg at first. Schrödinger, himself, stated,

It is hardly necessary to emphasize how much more agreeable it would be to represent a quantum transition as the passage of energy from one vibrational form into another, rather than to represent it as a jumping of electrons...I feel intimidated, not to say repelled, by what seems to me the very difficult methods [matrix mechanics] and by the lack of clarity.⁶⁸

Schrödinger moved from Zurich to Berlin to accept the Max Planck chair of theoretical physics and became a member of the Prussian Academy of Sciences. With the political change of parliament and the rise of Adolph Hitler, however Schrödinger became disgusted with German society and moved to Oxford, England. During these trying years, he shuttled back and forth between Germany and Great Britain, finally settling at the Institute for Advanced Studies in Dublin, Ireland. The remainder of Schrödinger's professional life was devoted to questions regarding the foundations of physics, cosmological queries, a grand unified theory and other philosophical inquiries.⁶⁹ Late in his life, with the aim of enticing Schrödinger back, Austria acknowledged him

⁶⁷ Gillispie, *Dictionary of Scientific Biography*, 219.

⁶⁸ *Ibid*, 220.

⁶⁹ The grand unified field theory, in physics, is an attempt to describe all fundamental forces (gravity, electromagnetic and strong and weak) in terms of a single theoretical framework, thus uniting classical and quantum laws.

with many awards and salutations. He did return to his favorite mountains, the Tyrolean Alps, and died January 4, 1961.⁷⁰

Schrödinger had developed a competing quantum theory. His method dealt with atomic phenomena using differential equations that the scientific community understood and used with ease. His method also gave an intuitive and physical picture of the movement of electrons around the nucleus. At play was a difference in the nature of methodology. Experimental physicists had an easier time incorporating Schrödinger's theory into experiment. Heisenberg's abstract notion of matrix elements was still theoretical and not easily verified through experiment. As mentioned, Heisenberg believed Schrödinger's first paper, "puts us [physics community] back into a state of mind which we have already overcome, and which has certainly to be forgotten."⁷¹ This "puts us back" refers to a traditional method of modeling natural phenomena with the differential calculus. Heisenberg and others from the Göttingen and Copenhagen schools knew that quantum theory had to be understood with a dramatically revolutionary method.

Heisenberg eventually realized the usefulness of using Schrödinger's theory as a mathematical tool. The differential equations employed by Schrödinger were powerful and could be used to describe the laws of nature. Heisenberg realized that using his own theory in certain situations, like calculating the shift levels in helium, would be extremely difficult, but Schrödinger's theory made the calculation much easier.⁷² Heisenberg made the transition to appreciating Schrödinger's theory through Born's statistical interpretation, but Schrödinger, himself, had a hard time accepting the new direction that

⁷⁰ Gillispie, *Dictionary of Scientific Biography*, 217-23.

⁷¹ AHQP Paper Documents, Werner Heisenberg file 23: 30.

⁷² *Ibid*, 24.

Born's interpretation was taking. He felt the theory was co-opted by other physicists. Schrödinger's anger for this turn in events only colored his opinion for Born's physical interpretation explaining reality through probability distributions. He felt strongly that Born molested his theory.

Wolfgang Pauli, a talented Vienna high school student was born April 25, 1900. His early studies concentrated on advanced mathematics in real analysis and in his free time, Pauli read Einstein's new Theory of Relativity. After his secondary academic experience, Pauli left for Munich to study theoretical physics under Arnold Sommerfeld. Heisenberg and Bethe were contemporaries and later Heisenberg and Pauli formed a close personal and academic relationship that continued throughout the 20s and 30s during which they both made their unique contributions to quantum theory.

Pauli showed his gifted nature when just twenty years of age he wrote a 250-page monograph analyzing the mathematical foundations of Einstein's Theory of Relativity. This work thrilled Sommerfeld and he was the teacher who introduced Pauli to the quantum theory of the atom. In 1945, Wolfgang Pauli was awarded the Nobel Prize and at a dinner in his honor in Princeton, he spoke these words about Arnold Sommerfeld, his mentor and teacher,

...I was introduced by Sommerfeld to the structure of the atom, somewhat strange from the point of view of classical physics. I was not spared the shock which every physicist, accustomed to the classical way of thinking, experienced when he came to know of Bohr's 'basic postulate of quantum theory' for the first time.⁷³

After receiving his doctorate "*Über das Modell der Wasserstoffmolekulations*" in 1922, Pauli began work on the anomalous Zeeman effect. His famous undertaking of the

⁷³ Nobel Foundation, *Nobel Lectures Vol. 3*, 27.

exclusion principle derived from this early work. Pauli explained the number of electrons that could occupy an atom. Pauli's discovery led to the further developments in quantum theory by Heisenberg, Schrödinger and Dirac, respectively. Essential to the further development of the group was Pauli's understanding and defining role of energy levels in an atom. His work was key because he refocused the group, not on stationary electrons but the transitions of electron energy levels.

Before World War II, Pauli lectured in Zurich at the Technical University, then transplanted himself to America, where Albert Einstein secured him a position at the newly organized Institute for Advanced Study in Princeton. This highly selective think tank was an independent institute separate from Princeton University. Their only objective was to develop thought, not teach. Eventually, Pauli and his family returned to Zurich, where he died suddenly at the age of fifty-eight.⁷⁴

Heisenberg and Pauli studied and worked together under all the leaders of the great groups, but even after their successes in the quantum revolution, they continued to work together in insightful ways. Their work in examining the interaction of radiation and matter were the first attempts to formalize a quantum mechanical event. Their work was a model for all cooperative groups, the long professional relationship that both of these men shared allowed for the advancement of atomic theory during the twenties.⁷⁵

Paul Adrien Maurice (P.A.M.) Dirac was born on August 8, 1902 in Bristol, England where he attended secondary school at Venturer's and university at Bristol. In 1921, after studying engineering, he received his Bachelors degree. Further study in

⁷⁴ Gillispie, *Dictionary of Scientific Biography*, 422-5.

⁷⁵ AHQP Paper Documents, Wolfgang Pauli file 1: 9-17.

mathematics led to an advanced degree at St. John's College, Cambridge. He began his academic career as a fellow at St. John's and later, 1932, became the Lucasian Professor of Mathematics at Cambridge.

Dirac involved himself in the great (quantum) group early in the 1920s, utilizing his mathematical background to examine the theoretical aspects of quantum mechanics. Two great achievements in this field led to the 1933 Nobel Prize, which he received jointly with Irwin Schrödinger and the same year as Werner Heisenberg. Dirac's first work was to simplify Heisenberg's quantum equations producing an equivalent mathematical scheme of non-commutative algebra for the analyses of atomic structures.⁷⁶ With the introduction of Schrödinger's wave equation was at odds with Einstein's relativity so he reconciled the two theories by inserting relativity into the wave equation. His achievements were met with numerous laurels from the scientific community and subsequently were elected a Fellow of the Royal Society in 1930 and awarded the Copley Medal of the Royal Society in 1961.⁷⁷

Heisenberg respected Dirac for his equivalence proof of the two seemingly opposite theories of quantum mechanics, wave and matrix mechanics. Dirac's proof motivated Heisenberg to evolve his understanding of how both of these theories worked together as practical mathematical tools.

⁷⁶ Non-commutative algebra was a basic and fundamental property of the new abstract mathematics of matrices. This property stated: if two elements, x & y , are of the set of real numbers, then x & y are said to be commutative under multiplication, if they satisfy the following condition: $x*y = y*x$. However, if x & y are matrices, then it is not the condition that they are commutative, unless x & y satisfy two conditions: they are diagonal matrices and both are the same dimension. An elementary proof of this property easily can be attained by examining the definition of matrix multiplication-

$$[x]_{ij} * [y]_{kl} = [z]_{il}$$

Multiplying XY and YX , ones results are two matrices with different dimension, therefore violating the commutative rule.

⁷⁷ Nobel Foundation, *Nobel Lectures Vol. 2*, 320-7.

The beginning of community formation occurred when Heisenberg gave lectures at Cambridge (1925). Dirac was young and stimulated by the ideas put forth by Heisenberg. Dirac's enthusiasm propelled him to work in this field and make outstanding contributions using his wonderful insight of mathematical structures and proofs. In an interview for the AHQP, Dirac emphatically stated that without Heisenberg and Schrödinger's work "I should never have done it by myself."⁷⁸

Ernst Pascual Jordan was born in Hanover on October 18, 1902. He prepared himself for a productive academic career by studying physics, mathematics and zoology at Göttingen University. In 1926, he became a *privatdozent* (lecturer) at the same university. Max Born was attracted to Jordan because of his keen mathematical skills and recruited him to be his assistant. Jordan played a pivotal role in shaping quantum theory by recognizing the mathematics employed by Werner Heisenberg as matrix elements, thus giving structure and formalism to Heisenberg's work. After Heisenberg published his new quantum theory, Jordan sought to convert the physics community and to popularize the new quantum mechanics with lectures and two books, *Elementare Quanten Mechanik* in 1929 and *Anschauliche Quanten theorie*s in 1936.

As Adolph Hitler assumed power in the post-Weimar years, Jordan believed that the Nazi radicalism could be tempered through scientific cooperation and appeasement. However, in 1936, with his book, *Die Physik des 20 Jahrhunderts*, he gives full credit to the advancement of modern physics and quantum theory to the leading scientists who were labeled by German nationalists as practicing "Jewish Physics" (Einstein, Planck,

⁷⁸ AHQP Paper Documents, P.A.M. Dirac file 27: 6; file 29: 32 and AHQP Paper Documents, Werner Heisenberg file 15: 5.

Bethe, etc.). His involvement with the Nazis was indirect and never approached conscious action against fellow Jewish physicists. During the post-war period, however, Jordan was heavily criticized for his actions.

Jordan's role in the great group to develop a system for quantum physics was essential. Without Jordan's mathematical expertise, the understanding of Heisenberg's work as the formation of a diagonal matrix may not of come at the time it did. Born and Jordan's cooperative enterprise and subsequent work with Hesienberg enabled them to see the connections that later became known as Heisenberg's matrix mechanics. Heisenberg respectfully remembers, "I had many discussion with Jordan, and I realized that he was very good."⁷⁹

Jordan's accomplishments and awards are numerous. In addition to work in quantum theory with matrix mechanics and electrodynamics, he advanced theoretical work in biophysics. He was a recipient of Max Planck and Gauss Medals and a member of the Academy of Letters and Sciences Mayence. Pascual Jordan died in Hamburg on August 8, 1980.⁸⁰

Conclusion

All the members, whether leaders, gifted individuals or associates, had great admiration for each other even if unpleasant remarks or criticisms went too far. In the end, the success of the group depended on the genuine respect found among this group of physicists.

⁷⁹ AHQP Paper Documents, Werner Heisenberg file 25: 11-2.

⁸⁰ A. Debus, ed., *World Who's Who in Science: A Biographical Dictionary of Notable Scientists from Antiquity to the Present* (A.N. Marquis Company, 1968), 894 and AHQP Paper Documents, Pascual Jordan (biography) file.

The larger community of scientists recognized that the groups out of Copenhagen and Göttingen had done something. The burden of proof had switched and the larger communities were accepting the new quantum theory, since most problems and contradictions had been eliminated. For the younger generation, it was an opportunity to take part in the beginning of a new idea and help spread it through writing and instruction. In 1929, as Heisenberg traveled to the United States to give a series of lectures, he found “already quite a number of groups extremely interested in this kind of problem.”⁸¹ The great group completed its objective of establishing a sound, coherent and logically consistent structure for understanding the electron.

Society’s focus and obsession on the solitary genius has created a cultural myth. Science involves the precise and orchestrated work of a community of individuals in collaboration with each other. During the development of quantum theory, Sommerfeld, Born, and Bohr recruited, organized, and directed a group of individual mathematicians, technicians, experimentalists, and theoreticians to create the group’s transcended community whose work led to the revolutionary discovery of particle physics. The groups creation through collaboration enlarged the science communities attempts to understand the turn of the centuries discoveries or anomalies that plagued physics.

Heisenberg participated in the construction of quantum theory. The unique effort and achievement by scientists associated with the Göttingen, München, and Copenhagen groups were incredible. Their accomplishments were due to a strong collaborative effort by not just one individual or group, but several groups of physicists working together and sharing ideas towards a common goal.

⁸¹ AHQP Paper Documents, Werner Heisenberg file 25: 9-15.

However, the final breakup of the various groups working on quantum theory came with the Second World War. The mutual trust and admiration shared within the international community of scientists began to break down as political and national lines were drawn and apolitical scientists were forced to take sides. Firm resolution on either side of the national line created mistrust and undermined any possible collaboration within the old group until the war was finished or possibly never. However, all the participants fondly remembered the collaboration and comradeship enjoyed by the M \ddot{u} nich, G \ddot{o} ttingen, and Copenhagen communities.

Heisenberg stayed in Germany to help his graduate students and associates, and not abandon them to a collapse of the German scientific community. He was now the leader of the new collaborative community just as Sommerfeld, Born, and Bohr had been in the 1920s. His chance to resurrect not the quantum community, but the feelings and accomplishments associated with collaborative science was before him. His chance meant staying in Germany and using any and all Nazi, Third Reich, and German military resources.

In 1941, Heisenberg visited Bohr to reconnect with his mentor and fond remembrances of the work he and others had done with quantum theory. He also, wanted his former mentor's advice as Bohr had done so many times in the past while they worked on his quantum theory and the Uncertainty Principle. The collaborative experiences of Heisenberg are important because they open up emotional and professional reasons and motivations for why he visited Bohr in Copenhagen.

CHAPTER FIVE

A PERFECT UNION OF MENTOR AND STUDENT

The Explosive Relationship of Werner Heisenberg and Niels Bohr

Friction, tension, miscommunication, and a general lack of understanding convey the relationship between Niels Bohr and Werner Heisenberg. That of father and son does not. Though these two scientists worked closely with each other, Heisenberg's personality often disrupted any possible close personal relationship. Heisenberg's interactions and relationships with other physicists confirm the tensions and friction often present with Heisenberg's professional interactions.

Werner Heisenberg's increasing social ascendancy combined with his father's academic achievements helped to facilitate his indoctrination into the competitive atmosphere of German culture. He competed academically and culturally with his brother and then later with society to achieve scientific and cultural status.¹

This chapter examines the emotional side of Werner Heisenberg. His upbringing and early adolescence taught him to be competitive at all costs for love and approval. These personality traits he took to university and later to the institutes of Göttingen and Copenhagen set him apart from his colleagues. Though Bohr took Heisenberg in as an assistant and worked with him as a collaborator, a distance between them existed because of Heisenberg's explosive and emotional nature.

¹ David Cassidy, *Uncertainty: The Life and Science of Werner Heisenberg* (W.H. Freeman and Company, 1992), 5.

Family and Adolescent Life

Heisenberg and his brother, Irwin, challenged each other for affection from their father so that he might look upon one of them with more pride and pleasure. They both competed in the academic and cultural arena. Heisenberg's older brother brought mathematics work home from the gymnasium and the two competed to see who was faster at the computation. These games were the first indication that Heisenberg had a special gift for mathematics.² Werner remembered how his father urged them both to compete. Heisenberg said of this competition, "Our father used to play all kinds of games with the two boys...So, when my brother had some mathematical problems...he [Augustus] tried to use these problems as a kind of game and find out who could do them most quickly..."³ Heisenberg learned the rewards of competition at an early age training his character and psyche to thrive on games of skill and intelligence.

In 1911, this love of competition followed Werner to his entrance into Max-Gymnasium where he attended the more advanced sections that were reserved for the more talented students. Irwin and Werner had one year between them in academic grades and with Werner striving in the advanced placement classes, the competition remained alive between them.⁴ The German tradition of gymnasium rewarded those students who excelled at academics and reinforced the idea that academics was one means of acquiring a heightened social status.

² Ibid, 14.

³ AHQP Paper Documents, Werner Heisenberg file 16: 1.

⁴ Cassidy, *Uncertainty*, 23.

The Heisenberg brothers continued to compete culturally as well as educationally for their father's approval. Augustus practiced opera and the boys accompanied him, with Irwin playing violin and Werner playing cello and piano.⁵ This type of competition created blinders so one had no loyalty to brother or associate, only self. The rivalry between Heisenberg and his brother, Irwin, laid the foundation for further social competition and the drive to lead others. Heisenberg joined the leadership in the German youth movement, a group identified as the Pathfinders. This was a vehicle for Heisenberg to practice and assume a leadership role over his peers. With the close of World War I, Heisenberg had coalesced as a leader among fellow gymnasium students and members in the youth movement.⁶

The family rivalry shaped and molded the explosive and moody temperament of young Heisenberg. This characteristic would affect his professional and personal relationships throughout his life among the scientific community. Later in Heisenberg's life, the intense competition was evident in the confrontations and explosions of temper with fellow and associate collaborators in the scientific world. Early in his professional physics career, Heisenberg clashed with fellow scientists. His colleagues thought he was brilliant but odd and too emotional at times. Heisenberg argued with experimentalist Wien on several occasions from dismissing the importance of experimental work to criticizing a colleague of Wien's. Heisenberg burst out with emotion and accused Born of defecting to Schrödinger's wave community. He also blamed Schrödinger for Born's actions.

⁵ Ibid, 14.

⁶ Ibid, 16, 65-8.

Besides the drive to excel in a social and academic context, the joining of a youth movement became a concrete idea for Heisenberg and his fondness to the "romantic and idealistic Germany" of the past.

The Professional Scientific Community

The first meeting between Bohr and Heisenberg took place at the Bohr festival where Heisenberg introduced himself in a brash manner. Bohr's co-authorship on the quadratic Stark effect of hydrogen inspired Max Born and his colleagues to invite him to speak. In 1922,⁷ after a summer of talks in Munich, Born invited Bohr to give a series of talks on his Stark paper.⁸ The new "brain waves" from all over Europe attended the Bohr festival.

Young Heisenberg was one of the 100 attendees that listened as Bohr explained his and Kramers' paper. A young Heisenberg, nineteen years old, lashed out in criticism during the question and answer period. Bohr was shocked as the audience was at the relatively unknown Heisenberg and his brashness. After the lecture was finished, Bohr asked Heisenberg, "Couldn't we go for a walk in the [forest] and have nice time together, and we must really come to the bottom of this problem."⁹ Bohr's considerable calm in asking Heisenberg to discuss the difficulties of his own theory and its recurring consistency problems sets the tone of this unique relationship and emphasized his leadership abilities in contrast to Heisenberg's temper.

⁷ This date of 1922 is cited by Robert Jungk in his work, "Brighter than a Thousand Suns," but is contradicted by an interview Heisenberg gave to Thomas Kuhn for the AHQP project. There could be discrepancies regarding earlier talks Sommerfeld took Heisenberg to, but for this argument, the crucial talk is Heisenberg's outburst of emotions and criticisms I am after. I have chosen to stick with the 1922 timeline for my purposes.

⁸ Sommerfeld took Heisenberg to Munich to listen to the summer colloquia. Heisenberg remarked that so many talented people attended these talks. People from Göttingen and Copenhagen were there and interested in the new topics of relativity and quantum theory. What amazed young Heisenberg was the talent in both fields of physics and mathematics with people such as Born, Hilbert, Bohr, Minkowski and Hund.

⁹ Robert Jungk, *Brighter than a Thousand Suns* (Harcourt, Brace, & World, Inc., 1956), 25-30 and AHQP Paper Documents, Werner Heisenberg file 16: 13-14.

Bohr's wife, Marguerite, remembers fondly all the assistants with whom Bohr himself felt a close personal connection. Bohr was good friends with the whole group, such as Kramers, Klein and Pauli. The only exception was Heisenberg, who often had difficulties with the group and Bohr himself. Bohr's wife and his son, Aage Bohr, referred to Heisenberg as strange and difficult at times, almost as though he was from a higher social class, but at other times pleasant enough.¹⁰ Though Heisenberg was prone to emotional outburst, he still saw Bohr as his mentor, as the "Pope." Bohr was a figurehead, a central authority on quantum topics and an arbiter for Heisenberg to solicit guidance and judgment.¹¹

Fru Bohr, Niels Bohr's wife, recalled the visits by Bohr assistants and the tension between Heisenberg and the others, particularly Bohr. "I [Fru] remember Heisenberg especially playing hide and seek out there [the gardens of Bohr's residence in Copenhagen]."¹² Though there was a familiarity between the Bohr and Heisenberg households, there was a feeling of unpleasantness that helped further the friction in their relationship. In a January 30, 1963 interview, Fru Bohr along with Aage Bohr, Leon Rosenfeld, and Thomas Kuhn discussed the relationships of all the prominent assistants that worked with Bohr in Denmark.

T. Kuhn: [assistants]...was that a really close personal relationship as well as a close professional relationship?

Fru Bohr: With Kramers that was a personal relationship; they were very good friends, yes. Oh, that was a very warm friendship; always until he died. And it was also with Pauli.

¹⁰ AHQP Paper Documents, Niels Bohr file 35: 17.

¹¹ Daniel Serwer, "Unmechanischer Zwang: Pauli, Heisenberg, and the Rejection of the Mechanical Atom, 1923-1925," Vol. 8 (1977), 237.

¹² AHQP Paper Documents, Niels Bohr file 35: 16a.

T. Kuhn: What about Klein and Heisenberg?

Fru Bohr: Oh, it was also with Klein, yes. Niels had that kind of relationship with most. Well, with Heisenberg, it was not so much— Heisenberg had some difficulties which came up occasionally. But then in between he was a pleasant man...But there was difficulties with Heisenberg.¹³

The underlying message of the interview tells of a relationship between the Bohr family, Bohr himself, and others with Heisenberg that was not a picture of warmth and familiarity among friends. A tension is present during this interview that Fru does not yet name, only that “there was difficulties with Heisenberg.”¹⁴ The assistants, with the exception of Heisenberg, enjoyed a close and warm professional and personal relationship with Bohr, and indirectly with the whole family. Bohr was the patriarch, the father who guided everyone who studied and worked in Copenhagen. Later in that same interview, Fru remembers a comment by the assistant, C. G. Darwin. Darwin coined an interesting term, “well-bred.”¹⁵ Fru states, “...Darwin, who was here [Copenhagen] once together with Heisenberg, said, he was pleasant [but] what you would call well-bred. I mean he had nice manners and was pleasant in that way.”¹⁶ Heisenberg was reserved in comparison to everyone else. “He was not open,” Fru stated during this interview, and “he could be unfair.”¹⁷ This reflection places the community’s attitude towards Heisenberg squarely as an outsider because of three qualities of temper: reservation, and the “well-bred” nature of his personality. His associates witnessed the romantic German character Heisenberg learned to emulate during his youth movement days. This character had an air of superiority over all others.

¹³ AHQP Paper Documents, Niels Bohr file 35: 17.

¹⁴ Ibid.

¹⁵ Ibid.

¹⁶ Ibid.

¹⁷ Ibid.

Enlarging the scope and viewing Bohr's and Heisenberg's relations with others helps to uncover the relationship and possible outcomes of arguments between Heisenberg and Bohr. A fundamental disagreement with values, politics, and scientific methods was not a breaking point in their friendship. Instead, a history of conflict among Heisenberg and his associates makes it easier to understand the conflict in his relationship with others and especially at the 1941 meeting in Copenhagen.

Tension and friction with Heisenberg and others and even with the friendly Bohr always existed. Heisenberg's German romantic upbringing, a sense of German historical tradition of greatness, coupled with his father's fierce indoctrinated competition, solidified Heisenberg's personality and possibly disruptive character. The 1941 confrontation in Copenhagen between Heisenberg and Bohr does not have to be analyzed as a unique event with out precedence. Scholarship concludes they had unique and affectionate relationship as student and mentor. However, this is a fond remembrance because Heisenberg's personality often placed their relationship on unstable ground. It was an event that had a history and that history kept both individuals upset and confused about the wartime meeting.

The academic relationship between Schrödinger and Heisenberg was nothing short of tense. They had developed competing ways of dealing with atomic events. Niether liked each other's views and urged other physicists to comply with their own favored formulas. At play was a difference in the nature of methodology, a contest of ideas between Sommerfeld's theoretical physics and Wien's experimental institute. Between these camps was a strong separation, because of the different fundamental approaches to practicing physics. These institutes could be unfriendly to each other even

though only separated physically by 100 yards of ground. Pauli once said, “Well, experimental physics is ninety percent extremely annoying.”¹⁸ The other side had that opinion of theory as well. Heisenberg was frustrated and disappointed about the angle Schrödinger was taking towards a classical interpretation. Heisenberg said of Schrödinger’s first paper, “Now Schrödinger puts us [physics community] back into a state of mind which we have already overcome, and which has certainly to be forgotten.”¹⁹ Heisenberg did not like Schrödinger’s ideas of wave mechanics, and he was vocal about it.

Heisenberg’s Conflict with Born and Schrödinger

In 1926, Schrödinger spoke at a colloquium at Wien’s institute, with Heisenberg in attendance. Heisenberg spoke out in criticism of Schrödinger’s idea. Wien was enthusiastic about Schrödinger’s new idea, since it preserved the casual ideas of classical physics and could be experimentally observed. So Wien attacked Heisenberg, “Young man you still have to learn physics, and it will be better if you sit down...[and] go learn physics before you talk to Professor Schrödinger in that way.”²⁰ Wien’s comments were harsh and conveyed the friction between the two camps, culminating in almost throwing Heisenberg out of the institute that day.²¹

Born’s and Heisenberg’s relationship involved tension and confrontation over theoretical constructions of quantum theory. Born received criticism for his statistical interpretation of wave mechanics from both Schrödinger and Heisenberg. In an interview

¹⁸ AHQP Paper Documents, Werner Heisenberg file 17: 16-7.

¹⁹ AHQP Paper Documents, Werner Heisenberg file 23: 30.

²⁰ AHQP Paper Documents, Werner Heisenberg file 16: 26.

²¹ Ibid.

for the AHQP, Born reflected on Schrödinger's anger and unhappiness with his interpretation of his work on the wave function.²² And in a similar interview, Heisenberg recollected, "...I did not like so much that Born went over to the Schrödinger theory... Schrödinger, as you know, wanted to throw out all the quantum jumps away and to say that there is no quantization."²³ At first, Heisenberg extended the contempt he had for Schrödinger to Born. Heisenberg's frustration with Born is understandable since Schrödinger's criticisms and statement of "no quantization" are essential components in Heisenberg's quantum mechanics. But the key is not contempt but the motivation it instilled in others to try and convince Schrödinger of the validity of the work Born had done by closing the divide between both camps.

Bohr, A Tension

After Schrödinger's visit, heated talks between Bohr and Heisenberg erupted when Bohr demanded that Heisenberg deal with Schrödinger's waves and the implications it had for quantum theory holistically. In rebuttal, Heisenberg only wanted to deal with his "mechanical scheme...and use Schrödinger's theory perhaps as a mathematical tool sometimes."²⁴ Heisenberg did not want to consider Schrödinger's interpretation of the "wave packet." Bohr was very frustrated because both of them used

²² AHQP Paper Documents, Max Born file 41: 28.

²³ AHQP Paper Documents, Werner Heisenberg file 22: 1-2.

²⁴ AHQP Paper Documents, Werner Heisenberg file 23: 14-6. An interesting note that cannot be left unsaid- Heisenberg's views of only wanting to use Schrödinger's "wave tools" and not to consider the physical (Schrödinger's) interpretation is contradicted approximately ten years after the interview with Thomas Kuhn for the AHQP. In a letter dated July 12, 1974, Heisenberg writes Prof. Edward McKinnon, "On page 63 you express the opinion that only Bohr felt the need for an (sic) physical interpretation of quantum mechanics, while other physicists, including myself, considered the mathematical scheme as a sufficient explanation of the phenomena. I believe I have always shared the opinion of Bohr..." This seeming contradiction, I believe, does not collapse any part of the great group and collaboration argument. If it is true of the later opinion, it just shows Bohr's influential powers of argument with one of his gifted individuals (AHQP microfilm 80: Heisenberg to McKinnon on July 12, 1974, pp. 1-2).

parts of each other's theories only when convenient, and he knew that both theories needed to be reconciled.

With the choice between two quantum theories, Bohr stressed the need for clarity twice, once with Schrödinger over his physical interpretation of wave mechanics and another time with Heisenberg, where he disagreed with Heisenberg's approach in constructing the Uncertainty Principle. Schrödinger and Heisenberg found it difficult to agree, especially since Heisenberg's loyalty were with his own theory and matrix calculus that did not examine wave packets. Bohr pushed however until there was a realization by Schrödinger and Heisenberg that inherent contradictions existed with both of their theories and that the final solution would be complicated. The search for answers continued with Bohr leading the group's efforts to understand the inconsistencies of quantum theory.

The friction inherent in the discussions between the matrix and wave theories is also apparent in Heisenberg's and Bohr's clarification of the Uncertainty Principle. In March of 1927, Heisenberg submitted a paper to *Zeitschrift für Physik* entitled "On the perceptual content of quantum theoretical kinematics and mechanics" that elucidated his Uncertainty Principle.²⁵ Real and serious disagreement between Bohr and Heisenberg over the Uncertainty Principle followed. Bohr held philosophical and theoretical objections to Heisenberg's explanation of this new development. Heisenberg felt frustrated because he did not know how to handle criticism, and lashed out at Bohr in a burst of emotion, forcing Bohr to leave Heisenberg's company. Bohr left for Norway to

²⁵ Heisenberg throughout the AHQP archives refers to his development as the uncertainty relations but other sources have two somewhat different names, uncertainty principle or indeterminacy principle. All three refer to Heisenberg's part in the Copenhagen interpretation (Cassidy, *Uncertainty*, 226).

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During this separation, Heisenberg "thought that this thing with the Uncertainty Principle would be the right answer."²⁷ Heisenberg began working on the relationship of velocity and position. Before Bohr's return, he had developed the basics of the Uncertainty Principle. He anticipated that Bohr would be angry so he sent his paper to Wolfgang Pauli for his opinion. Pauli was "extremely enthusiastic."²⁸ The disagreement intensified when Heisenberg went ahead and sent his paper in for publication. Even though Bohr had demanded adjustments because he thought, the idea was not ready for publication. Misinterpreting Bohr's thoughts, Heisenberg believed the theory was ready and Bohr would approve "especially since Pauli's letter had convinced [Heisenberg] that

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²⁶ AHQP Paper Documents, Werner Heisenberg file 23: 16

²⁷ Ibid.

²⁸ AHQP Paper Documents, Werner Heisenberg file 23: 16. Wolfgang Pauli had been a sounding board for Heisenberg in the past. Heisenberg trusted Pauli's valuable and talented critical analysis. Heisenberg hoped that if Bohr understood that Pauli consented that parts of the paper could be valid.

quite clear what I had written.”³¹ This tension centered on Bohr’s disagreement with Heisenberg’s analysis of the Gamma ray microscope and the correct aperture for the instrument.³² Again, similar to Heisenberg’s problem with experimental physics in his doctoral examination, Bohr did not agree with Heisenberg’s experimental analysis. This criticism was too much for Heisenberg. The scientific community praised his insightful work, not criticized it. Heisenberg’s emotional reaction, in turn, infuriated Bohr. He showed Bohr, through his actions, that he was furious with Bohr’s comments and that he did not handle criticism from an elder, even Bohr. Remembering that tense situation, Heisenberg tells how “Bohr tried to explain that it was not right and I should not publish the paper. I remember that it ended with my breaking out in tears because I just could not stand this pressure from Bohr.”³³ The pressure and criticism created a power struggle in Bohr and Heisenberg’s relationship. Heisenberg understood Bohr to be his superior, intellectually, culturally, and scientifically. He struggled all his life for approval from his father, gymnasium instructors, university professors and ultimately the man he sought approval from the most, Bohr. Heisenberg’s difficulties with criticism and approval from superiors stemmed from the intense competition he actively participated in.

In Bohr’s method of correction, he maintained that to arrive at Heisenberg’s conclusion, one must interpret the situation through the concept of a wave and not a particle. This adjustment to Heisenberg’s theory changed the scientific conception of matter through wave and particle. This change frustrated Heisenberg and further heated discussions eventually brought Heisenberg to understand Bohr’s idea of

³¹ Ibid.

³² Ibid.

³³ Ibid.

Complementarity.³⁴ Then Bohr channeled Heisenberg's anger and self-doubt into motivating both of them to compromise and comprehend each other's view. Bohr relented philosophically to the idea of indeterminacy and the loss of classical causality, and Heisenberg revisited the instrumentation of the gamma ray microscope.³⁵ Ultimately, this understanding led to the collaborative publications that became the Copenhagen Interpretation.³⁶

Bohr insisted that the particle and wave nature of an electron shows itself in every experiment, depending on what the experimenter decides to look for. This clash of personalities lasted well into the Christmas holidays. During these holidays Heisenberg wrote to Dirac from Copenhagen explaining the idea of the Uncertainty Principle. In his letter, Heisenberg used the idea of scattering light and not incident light, thus supporting Bohr corrections as to how the thought-experiment worked. Further, near the end of the letter, Heisenberg mentioned to Dirac that Bohr's idea of a wave nature is also involved in his experiments and theory. The only comment Heisenberg can make to Dirac is that "of course he [Prof. Bohr] is quite right."³⁷ Heisenberg commented later that he knew why Schrödinger took ill during the visit he had with Bohr.³⁸

Heisenberg wrote his paper on the Uncertainty Principle while tension existed between him and Bohr. The tension involved a fundamental disagreement of the

³⁴ Complementarity: An assertion that states both wave and particle natures are present, simultaneously, in any experiment. The experimenter introduces how nature expresses itself within the experiment, wave or particle. It is with this outcome that the uncertainty relations manifest itself by expressing the wave or particle nature of matter (J. Thewlis, eds., *Encyclopedic Dictionary of Physics: General, Nuclear, Solid State, Molecular, Chemical, Metal and Vacuum Physics, Astronomy, Geophysics, Biophysics, and Related Subjects Vol. 2*, (Pergamon Press, 1961), 2-4).

³⁵ AHQP Paper Documents, Heisenberg File 19: 13-4.

³⁶ AHQP Paper Documents, Werner Heisenberg file 23: 4-18.

³⁷ AHQP microfilm 80: Dirac private collection. Heisenberg letter to Dirac on December 27, 1927, pp. 1-2.

³⁸ Cassidy, *Uncertainty*, 240-43.

quantum problem, philosophically and methodologically. Heisenberg, satisfied with his mechanics, refused any other mathematical schema, including Schrödinger's wave mechanics, until his theory still proved inadequate and problematic. Bohr believed that wave and corpuscular theories must be used in tandem with each other to explain atomic events. Bohr attempted to convince Heisenberg of his physical interpretation and solution. Heisenberg's pride of his own accomplishment, similar to his adolescent years, blinded him to any other possibilities. The German indoctrination of culture forced these blinders not to compromise. His actions can be seen as childlike. He wanted praise and reward for his theoretical construction but was offended at the slightest unsolicited criticism. Heisenberg's respect and admiration for Bohr, moreover, like his love for his father, created frustrations and sadness when Bohr did not wholly accept Heisenberg's Uncertainty Principle.

The arguments between Bohr and Heisenberg began with trying to understand the essential problems of quantum mechanics. Heisenberg wanted to

start entirely from the mathematical scheme of quantum mechanics and use Schrödinger's theory perhaps as a mathematical tool sometimes but never enter into Schrödinger's interpretation...I will try to follow that to the extreme and to see whether I cannot hope to predict everything from that scheme. Later on I will try to understand what the waves of Schrodinger mean.³⁹

Heisenberg did not understand, or want to understand, the benefits of wave theory. Bohr, however, did. He wanted to understand the nature of both the particle and the wave. Bohr believed the solution to quantum theories inherent inconsistency might be solved between these seeming contradictory theories. This work began Bohr's

³⁹ AHQP Paper Documents, Werner Heisenberg File 23: 14-6.

formulation of his ideas on Complementarity.⁴⁰ They both analyzed the problem from different angles and so agreement was hard, but not impossible. Heisenberg's pride, fostered by winning youthful and adolescent competitions, fueled the tension between them. Heisenberg's emotional and prideful attachment to his theory created a deficit to his professional and theoretical advancement.

Friction and tension existed between Bohr and Heisenberg. At times, they worked closely together in Copenhagen and both admired each other for their scientific skill. However, Heisenberg's German social background led to a culture of competition for him. Scholarship portrays their personal relationship as one of father and son but I disagree. The recollections of Bohr's family suggest that there existed uneasiness with Bohr and all his assistants in their dealings with Heisenberg. Werner Heisenberg's desire for social status led to the temper and motivation that estranged him from his colleagues. This emotional side of Heisenberg also placed an emotional distance between him and Bohr. His aggressive, competitive personality multiplied the explosive and emotional nature that ultimately led to the argument at Copenhagen with Bohr. In 1941 their meeting was the last of their professional collaboration.

⁴⁰ Ibid, 15.

CHAPTER SIX
COPENHAGEN, REVISITED

Heisenberg's motivation, intentions, and actions revolved around a set of variables that when examined holistically presents a clearer picture on his life decisions and the 1941 meeting. In this study, Heisenberg's uncertainty principle serves as the guiding instrument for analyzing these variables. A clearer picture results, but complete certainty is not attained. For example, in 1941, what conversation did Bohr and Heisenberg have in Copenhagen that upset both of these men, forced Heisenberg to leave early, and stopped communication until several years after the war? The tension and frustration did not disappear with the Allied victory but required time and space, allowing feelings to mend with the fading memories of the disturbing event. These critical periods can serve as variables for understanding the 1941 meeting by analyzing it with the Uncertainty Principle as a metaphor. These variables encompass the revolutionary development in quantum physics, the political and social upheaval of Germany from World War I to the rise and fall of Hitler's Third Reich, the collaborative construction of science by the Göttingen, München, and Copenhagen communities, and the professional and personal relationship between Bohr and Heisenberg.

Max Planck's mathematization of the constant h , known as Planck's constant, began the physics revolution by addressing anomalies not yet understood by the scientific community. His mathematical model led creative physicists to solve existing problems during the twentieth century. The next key advancement was Albert Einstein's work on

the photoelectric effect and the describing of light as composed of quanta. The quanta conception changed physicists' understanding of the nature of light and affected the direction of future quantum research. Niels Bohr presented the scientific community with a model of the atom, which provided the next generation of physicists with a working visual and computational model. The community strove to match real world data with Bohr's model. Their work provided insight into how nuclear forces interacted, then they made adjustments to theory and developed better atomic computational models.

This earlier work laid the foundation for the revolution by a young group of students led by Arnold Sommerfeld, Max Born, and Niels Bohr who made incredible theoretical breakthroughs. Bohr's Correspondence Principle changed the community's focus from stationary to energy transitions of electrons. This significantly influenced Wolfgang Pauli's Exclusion Principle and firmly set the atom's computation model for simple structures, such as hydrogen. The work of Kramers and Heisenberg on the dispersion theory set the stage for Heisenberg's own reconfiguration of the Fourier expansion series in matrix form. Born and Pascual Jordan recognized this as matrix algebra and solved any internal problems Heisenberg had with his new formulation. These three men continued to work out a complete, formal system of matrix mechanics in their seminal "three-man" paper explaining the complex details to the scientific world. The new quantum theory had been created!

Heisenberg's professional success influenced the manner in which he saw himself, the world, and his unique role in it. He was a young, successful scientist that was lecturing at numerous universities and visiting research facilities discussing his new theory. The positive public response to his theory reinforced the notion that he belonged

to a special social class of Germans, the scientist. The class hierarchy that society supported allowed Heisenberg to feel superior to all other citizens, feelings that shaped his actions.

Political and Social Variables

Heisenberg's childhood was full of romantic visions and stories of Germany's great past. His father and grandfather were academics who established the Heisenberg family in a higher German social class. Heisenberg went to the gymnasium with awareness of the special status his future entailed. Any actions had to be rationally thought out and checked, since it would affect his university career. His future was bright, as long as society respected and supported his social stature linked to the past Wilhelmian era. His wonder and admiration towards the noble German past influenced his decision to join the German youth movements, provided food during military blockades, and assisted people affected by the terrible years of World War I.

The end of the Great War affected all Germans as they tried to cope with food scarcity, energy shortages, and economic hardships. These experiences left a lasting impression as Heisenberg matured into a young man. The Weimar government did not satisfy Heisenberg or other Germans, who experienced the hardships of the war and wanted a future like times of old. The past reinforced their sense of German greatness and the Weimar Republic was falling short of earning their respect and political support. Though Heisenberg saw himself as apolitical, he did participate and believed in the youth movement's frustration and unsatisfied feelings with the new democracy. These

hardships during the republic prepared Heisenberg and the public for Adolph Hitler's national socialist party.

Contemporary society understands Germany during World War II with shock, understandable due to the crimes of the Nazi government. However, to understand the complex political environment requires examination of the social and political context of Germany. German society was falling apart socially, politically, and culturally. Hitler represented the great German past and was welcomed by large segments of society. Heisenberg, apolitical, understood Hitler's party as capable of fixing society's immediate problems and not until he himself was attacked did Heisenberg change his political stance. Because a majority of its founders and followers were Jewish, Aryan physics challenged the advances of relativity and quantum mechanics. Not only did Heisenberg sense the coming assault on his physics and his community, but also a large part of Germany's most talented researchers, scientists, and students were immigrating and eventually were segregated out of the scientific community based on their racial identity. Heisenberg decided to fight the assault as an assault on his status and livelihood.

Heisenberg's class status and honor came into conflict. He had several opportunities open to him, but only one choice allowed him to retain his status and importance. Heisenberg was offered many appointments to leave Germany, but to leave meant never coming back with full status and authority. To stay and not fight the battle with the Aryan movement meant to live in Germany as a second-class citizen. His only real option was to fight this attack upon himself and his associates. This change in his apoliticalness also motivated Heisenberg to continue working within the government's structure. State collaboration provided him with funding, students, and a viable future for

rebuilding German science. However, to attain this objective meant Heisenberg becoming politically aware, motivated, and active.

Collaborative Science

Heisenberg participated in the construction of quantum theory. The unique effort and achievement by scientists associated with the Göttingen, München, and Copenhagen groups were incredible. Their accomplishments were due to a strong collaborative effort by not just one individual or group, but several groups of physicists working together and sharing ideas towards a common goal.

Heisenberg witnessed the powerful union of these groups and what these groups achieved when working in collaboration. From the beginning of university to Heisenberg's first teaching appointment, he and others like him were recruited, selected for special research, and directed towards progressive scientific development. Without the collaborative team of Born, Jordan, and himself, matrix mechanics would not have been recognized, developed, and solidified. Heisenberg's talented work needed the help of these other men who influenced, critiqued, and modified his quantum ideas.

When under the tutelage and supervision of Sommerfeld, Born, and Bohr, Heisenberg experiences left a deep impression of the possibilities of a collaborative group. Heisenberg fondly viewed the successful development of quantum theory with his fellow, collaborative associates. He desperately wanted the same scientific community for German science after the war. After the war, he hoped to reconcile his actions with the international scientific community and restore German prominence, as a leading force in the creation of science. Heisenberg's motivation was to develop a collaborative

postwar German program. He needed funding, researchers, and students. His involvement with the Third Reich allowed him to successfully accomplish this objective by securing funding, associates, and political protection.

Heisenberg and Bohr:
Professional, Personal, and Private

Heisenberg and Bohr shared many fruitful, joyful, and often stressful moments. Bohr recognized Heisenberg's talents and helped nurture Heisenberg's scientific development. Heisenberg understood and recognized their student/mentor relationship, but often struggled with Bohr's advice and criticism through emotional explosions.

Demanding periods often complicated their relationship. Arguments were not uncommon when the two discussed and critiques their collaborative works and often discussions erupted in anger and frustration, leading Bohr wisely to separate. Though these incidents required time apart, Heisenberg often immediately sent postcards apologizing for his outbursts and disrespectful behavior. While scholarship refers to their relationship as fatherly and especially close, this was not the case. Heisenberg's personality and temper, influenced by German romanticism and idealism, set him and Bohr apart. Bohr had affections for Heisenberg, but these emotions were based on a professional relationship and tempered with caution based on the emotional and disruptive outbursts of Heisenberg.

1941 Copenhagen Meeting

What actually happened during the secret meeting between Bohr and Heisenberg? Can we know the details with complete certainty? The answer is no, because that

entails knowing and recording every word said that the participants themselves cannot even remember. However, limiting the uncertainty is possible by examining several important variables that represent critical periods of influence in Heisenberg's life.

What importance does the 1941 meeting hold? The evaluation of the four square variables are not the only factors that could be analyzed. An examination of other elements could expand our understanding of the meeting more thoroughly. Just as mathematics expands the number of variables in a model to capture the finer structure of reality, so can the historian. By identifying the critical aspects affecting historical actors one can reduce the imprecision of interpreting an event. The key lies with awareness of the historical actor's motivation and the cultural values influencing the historian.

The examination of German culture, politics, and history are essential to understand Heisenberg's development from youth to adulthood. Examining his relationships with the broader community of scientists narrows the uncertainty further. Analyzing Bohr and Heisenberg friendship and professional actions also limits the questions one might ask regarding their meeting.

In 1941, Heisenberg and Bohr met. Their conversation itself was vague and uncertain, but using Heisenberg's Uncertainty Principle as a guiding metaphor to probe these square variables brings clarity into focus. Heisenberg spoke of his pride in Germany, its possible victory against the Allies, and his unquestionable certainty of purpose in his atomic research program. He spoke with a strong German conviction and did not politely avoid any comments on Denmark's political existence. The vigor and enthusiasm he used was assertive, but Heisenberg had to make his point. Heisenberg

used strong language to get his argument across, sparing no one's feelings. Heisenberg was being Heisenberg.

Bohr had no alternative but to refuse any discussion with Heisenberg or acceptance of Heisenberg's wartime position that led to acquiescence with Hitler's Germany. The country he had known was no more and his own freedom was in jeopardy as he and Heisenberg met. Heisenberg's tone and topic offended Bohr. The frustration Bohr felt was not new, for he and Heisenberg had had these explosive discussions before. Many times during the twenties, they had argued over theory and its philosophical implications. Part of the situation had not changed; they were still arguing over philosophical implications, but the topic was the politics involvement in particle physics not theoretical discussions in quantum theory.

The interpretation of the 1941 Copenhagen meeting is fraught with difficulties. Not only are records not existent, but also there are psychological barriers in evaluating Heisenberg's motivations and actions. There can be no absolute knowledge, but the indeterminacy can be minimized. Without this knowledge, moral judgments cannot be made until an attempt to understand why Heisenberg's intentions, motivations or actions affected his path.

Scholars should ask two central questions to understand Bohr's and Heisenberg's 1941 meeting. What did Heisenberg say that offended and upset Bohr, and what did Heisenberg not get to say? Using Heisenberg's Uncertainty Principle as a metaphor allows for the clarification of their meeting. These variables lead to a conclusion that Heisenberg, because of his character formed by German culture and scientific success, and influenced by the German political situation, offended Bohr enough to temporarily

end their professional and personal friendship. This inference answers the first question without knowing the exact phrase or words that upset Bohr.

The second question is harder to unravel because of the difficulty of evaluating a historical figure's intentions and motivations. My metaphor suggests there were two questions or statements that Heisenberg did not get a chance to ask Bohr that September evening. It also can answer three other questions that scholars have asked in the past regarding their meeting. Scholars postulated that Heisenberg wanted to ask Bohr three other questions and statements: would Bohr join him in Germany on his atomic project, did Heisenberg intend to inform Bohr of his delaying actions because he did not want the Nazis in possession of a powerful atomic weapon, and was he attempting to convince Bohr for his help in delaying the Allied atomic bomb effort?

My model clarifies the intent of Heisenberg, and suggests that Heisenberg had good reason not to have asked these questions. First, Heisenberg would not have asked Bohr to join his research team. Heisenberg did not need or want an extra prominent scientist challenging him for power of his group. Germany after the war would be his Germany. The scientific community would be there for him to construct and to lead. His need was to build and run the future of German science, not to share that leadership role. Second, Heisenberg was not delaying his research to sabotage the Nazi bomb project. Heisenberg made gross errors on the critical mass calculation needed to fission U235 and sustain an explosive chain reaction. His calculations were in the tons, where the correct calculation by Rudolf Peierls and Otto Frisch placed the amount much, much smaller. Heisenberg had problems in experimental technique and calculations. His strong point lay in theoretical foundations and mathematical modeling of quantum phenomena. Last,

Heisenberg did want Bohr's assistance in delaying the acquisition of atomic weapons. He wanted Germany to win their war of conquest. The social and political variables illustrate Heisenberg's adolescent experiences of World War I and the Weimar Republic. He wanted Germany to begin their new future without a deficit in every social and scientific aspect. Though he may have had reservations over the use of atomics, he did not want Germany defeated.

Heisenberg's main concern was to ask questions regarding the theoretical aspects of nuclear fission and the possible technical construction of a nuclear reactor. He informed Bohr of his research and his team's accomplishments. His personality required that he do so for praise from his superiors. And Bohr was still the Pope. The questions he asked revolved around problematic details of fission research. Bohr would not be asked to question or critique Heisenberg's accomplishments and if this happened, Heisenberg's reaction definitely would have been emotional and disturbing.

Heisenberg's second intention was to distance himself, in Bohr's mind, from the Nazi leadership. Heisenberg wanted to formulate an excuse for his remaining in Germany during Hitler's Third Reich. He reminded Bohr of his efforts defending their colleagues and friends who were Jewish and his obligation to the young graduate students remaining at German universities and institutions. Unfortunately, this political conversation led to the German occupation of foreign countries and Heisenberg's acquiescence of Poland's and possibly Denmark's occupation. He defended his actions. He served the German state because of his cultural indoctrination and partly out of sheer arrogance. Heisenberg was a product of Germany with all its cultural and political

underpinnings, he did not occupy a higher ethical plain, as did other influential physicists.

In the end, Heisenberg was a man of Germany.

MANUSCRIPTS CONSULTED

Archives for the History of Quantum Physics, Paper Documents, Office for History of Science and Technology, University of California, Berkeley (AHQP).

Archives for the History of Quantum Physics, Microfilm Documents, Office for History of Science and Technology, University of California, Berkeley (AHQP).

Bohr Scientific Correspondences, Office for History of Science and Technology, University of California, Berkeley (BSC).

Niels Bohr Institute, Copenhagen, Denmark. Niels Bohr Archive Paper Documents. The documents were retrieved from www.nbi.dk/NBA/papers/docs/d01tra.htm (3/13/2004).

Nobel Museum archives, Nobel Foundation. The documents were retrieved from www.nobel.se/index.html (3/25/2004).

The Manhattan Project Heritage Preservation Association, Inc. Archives. The document can be viewed at www.werner-heisenberg.uh.edu/Copenhagen.htm. (3/13/2004).

BIBLIOGRAPHY

- Abraham, David. "Consisting Hegemony: The Bourgeois Crisis of Weimar Germany." *The Journal of Modern History* Vol. 51, no. 3 (1979): 417-33.
- Beller, Mara. "Matrix Theory before Schrödinger: Philosophy, Problems, Consequences." *Isis* Vol. 74, no. 4 (1983): 469-91.
- Bennis, W. & Biederman, P. *Organizing Genius*. Addison-Wesley Publishing Company, Inc. New York: New York, 1997.
- Bernstein, Jeremy. *Hitler's Uranium Club: the Secret Recordings at Farm Hill*. New York: American Institute of Physics Press, 1996.
- Beyerchen, A. *Scientists under Hitler: Politics and the Physics Community in the Third Reich*. New Haven: Yale University Press, 1977.
- Bohr, Niels. *The Philosophical Writings of Niels Bohr*. Woodbridge: Ox Bow Press, 1998.
- Born, Max. *My Life. Recollections of Nobel Laureate*. New York: Charles Scribner's & Sons, 1978.
- . *Physics in My Generation: A Selection of Papers*. London: Pergamon Press, 1956.
- Cahan, D. "The Institutional Revolution in German Physics, 1865-1914." *Historical Studies in the Physical Sciences* Vol. 15, part 2, (1985): 1-66.
- Cassidy, David. *Einstein and Our World*. Amherst, N.Y.: Prometheus Books, 1998.
- . *Uncertainty: The Life and Times of Werner Heisenberg*. New York: W. H. Freeman, 1992.
- Childers, Thomas. "The Social Language of Politics in Germany: The Sociology of Political Discourse in the Weimar Republic." *The American Historical Review* Vol. 95, no. 2 (1990), 331-58.
- Compton, Arthur. "A Quantum Theory of the Scattering of X-rays by Light Elements." *The Physical Review* Vol. 21, No. 5 (1923): 483-502.

- Debus, A. éd. *World Who's Who in Science: A Biographical Dictionary of Notable Scientists from Antiquity to the Present*. Chicago: A.N. Marquis Company, 1968.
- Dirac, P.A.M. "On the Theory of Quantum Mechanics." *Proceedings of the Royal Society of London* Vol. 112, no. 762 (1926): 661-77.
- Darwin, C. G. "The Uncertainty Principle." *Science*, Vol. 73, no. 1903 (1931): 653-60.
- Dresden, Max. *H. A. Kramers: Between Tradition and Revolution*. London: Thomas Nelson, 1987.
- Eckert, M. "Propaganda in Science: Sommerfeld and the Spread of Electron Theory of Metals." *Historical Studies in the Physical Sciences*, Vol. 17, part 2 (1987): 191-234.
- Forman, Paul. "Weimar Culture, Causality, & Quantum Theory, 1918-1927: Adaptation by German Physicists & Mathematicians to a Hostile Intellectual Environment." *Historical Studies in the Physical Sciences*, Vol. 3 (1971): 1-116.
- Frayn, Michael. *Copenhagen*. New York: Anchor Books, 1998.
- A. P. French and P. J. Kennedy, eds., *Niels Bohr: A Centenary Volume*. Cambridge: Harvard University Press, 1985.
- Gay, Peter. *Weimar Culture: The Outsider as Insider*. New York: Harper & Row Publishers, 1968.
- Gillispie, Charles. *Dictionary of Scientific Biography, Vol. 1-18*. New York: Charles Scribner's & Sons, 1970.
- Goudsmit, Samuel A. *Alsos*. New York: Henry Schuman Inc., 1947.
- Hendry, John. *The Creation of Quantum Mechanics and the Bohr-Pauli Dialogue*. Dordrecht: Reidel, 1984.
- Heilbron, John. *Literature on the History of Physics in the 20th Century*. Berkeley: University of California Press, 1981.
- Heisenberg, Elizabeth. *Inner Exile: Recollections of a Life with Werner Heisenberg*. Boston: Birkhauser, 1984.
- Heisenberg, Werner. (1975). "Development of concepts in the history of quantum theory." *American Journal of Physics* Vol. 43, no. 5, (1975):125-30.

- . *Encounters with Einstein and Other Essays on People, Places, and Particles*. Princeton: Princeton University Press, 1983.
- . *Physics and Beyond; Encounters and Conversations*. New York: Harper & Row, Publishers, 1971.
- . *Physics and Philosophy: The Revolution in Modern Science*. New York: Harper & Row, Publishers, 1958.
- Hund, Friedrich. *The History of Quantum Theory*. New York: Barnes & Noble, 1974.
- Irving, David. *The German Atomic Bomb: The History of Nuclear Research in Nazi Germany*. New York: Simon & Schuster, 1967.
- Jammer, Max. *The Conceptual Development of Quantum Mechanics*. New York: McGraw-Hill, 1966.
- . *The Philosophy of Quantum Mechanics: The Interpretations of Quantum Mechanics in Historical Perspective*. New York: Wiley, 1974.
- Jungk, Robert. *Brighter Than a Thousand Suns: A Personal History of the Atomic Scientists*. New York: Harcourt, Brace, & World, Inc., 1956.
- Kater, Michael. "The Work Student: A Socio-Economic Phenomenon of Early Weimar Germany." *Journal of Contemporary History* Vol. 10, no. 1 (1975): 71-94.
- Kelves, Daniel. *The Physicists: The History of a Scientific Community in Modern America*. New York: Alfred A. Knopf, 1978.
- Laqueur, Walter. *Weimar: A Cultural History, 1918 - 1933*. New York: G. P. Putnam's Sons, 1974.
- MacKinion, Edward "Heisenberg, Models, and the Rise of Matrix Mechanics." *Historical Studies in the Physical Sciences* Vol. 8, 1977: 137-88.
- Mehra, Jagdish. *The Solvay Conferences Physics*. Dordrecht: Reidel, 1975.
- . *The Historical Development of Quantum Theory, vol. 1-5*. New York: Springer, 1982.
- Nobel Foundation. *Nobel Lectures: Including Presentation speeches and Laureates' Biographies: Physics 1942-1962*. 4 Vols. Amsterdam: Elsevier Publishing Company, 1964.

- O'Flaherty, James. "Werner Heisenberg on the Nazi Revolution: Three Hitherto Unpublished Letters." *Journal of the History of Ideas* Vol. 53, no. 3 (1992): 485-9.
- Pais, Abraham. *The Genius of Science: A Portrait Gallery*. Oxford: Oxford University Press, 2000.
- . *Niels Bohr's Times: In Physics, Philosophy, and Polity*. Oxford: Clarendon Press, 1991.
- Pauli, Wolfgang, ed. *Niels Bohr and the Development of Physics*. London: Pergamon, 1975.
- . "On the Connexion between the Completion of Electron Groups in an Atom with the Complex Structure of Spectra." In *The Old Quantum Theory*, ed. ter Haar, D., 84-203. Oxford: Pergamon Press, 1967.
- . "Über den Zusammenhang des Abschlusses der Elektronengruppen im Atom mit der Komplexstruktur der Spektren" *Zeitschrift für Physik* Vol. 31 (1925): 765-83.
- Powers, Thomas. *Heisenberg's War: The Secret History of the German Bomb*. New York: Alfred A. Knopf, 1991.
- Regis, Ed. *Who Got Einstein's Office? Eccentricity and Genius at the Institute for Advanced Study*. New York: Addison-Wesley Publishing Company, 1987.
- Rose, P. *Heisenberg and the Nazi Atomic Bomb Project: A Study in German Culture*. Berkeley: University of California Press, 1998.
- Scott, Joan. "On language, gender, and working class History." *International Labor and Working-Class History* Vol. 31 (1987): 39-45.
- Segré, Emilio. *From X-rays to Quarks*. San Francisco: W.H. Freeman & Co, 1980.
- Sereny, Gitta. *Albert Speer: His Battle with Truth*. New York: Vintage, 1995.
- Serway, R. *Physics for Scientists and Engineers, with Modern Physics*. New York: Saunders College Publishing, 1983.
- Serwer, D. "Unmechanischer Zwang: Pauli, Heisenberg, and the Rejection of the Mechanical Atom, 1923-1925." *Historical Studies in the Physical Sciences* Vol. 8 (1977): 189 - 256.

Stuewer, Roger. "On Compton's Research." In *Essays in Memory of Imre Lakatos*, Ed. Cohen, R.S. *Boston Studies in the Philosophy of Science* Vol. 39 (1976): 617-33.

---. *The Compton Effect: The Turning Point in Physics*. New York: Science History Publications, 1975.

Thewlis, J. eds. *Encyclopedic Dictionary of Physics: General, Nuclear, Solid State, Molecular, Chemical, Metal and Vacuum Physics, Astronomy, Geophysics, Biophysics, and Related Subjects, Vol. 1-9*. New York: Pergamon Press, 1961.

Walker, Mark. "Werner Heisenberg's Foreign Lectures under National Socialism." *Historical Studies in the Physical Sciences* Vol. 22, part 2 (1992): 339-90.

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