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CLIFFORD GLENWOOD SHULL
1915—2001

A Biographical Memoir by
ROBERT D. SHULL

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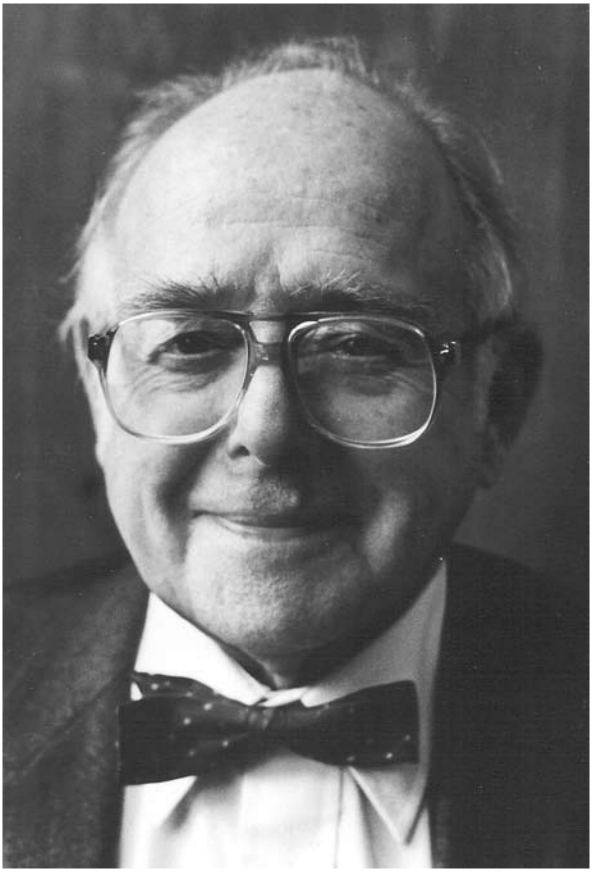
Biographical Memoir



Clifford Shull

CLIFFORD GLENWOOD SHULL

September 23, 1915–March 31, 2001

BY ROBERT D. SHULL

CLIFFORD GLENWOOD SHULL WAS ELECTED to membership in the National Academy of Sciences in 1975. He had earlier, in 1956, been admitted to the American Academy of Arts and Sciences, and would in 1994 be awarded the Nobel Prize in Physics. These and other honors were in recognition of his pioneering accomplishments in the development of neutron scattering techniques for atomic and magnetic structure determination. The Nobel Prize was awarded 50 years after the beginning of his discoveries and 15 years after he had retired as an emeritus professor of physics at the Massachusetts Institute of Technology. In this case the scientific community had ample time to see the ramifications of his achievements. Between 1946 and 1994, several other Nobel Prizes were awarded to individuals for discoveries or predictions verified partially through the use of neutron scattering methods.

The Nobel Prize was not something to which Cliff aspired. "The achievements of past winners are so phenomenal it's beyond one's scope to think of being in that class. I certainly had no feelings of delusion about joining such people," expressed Cliff to videographers for the Nobel Foundation just after announcement of his selection as one of the 1994 recipients.[1] Cliff's humility was a personality trait that governed the way he approached science, and it was a characteristic that set him apart from others.[2] One of his great sorrows was that Ernest Wollan, a colleague who pioneered the development of neutron scattering with him in the early years, was not alive in 1994 to share the Nobel Prize with him.[3]

As with most past events when one looks back at the history leading up to them, it is surprising they ever occurred since so many other preliminary things had to occur first, and in just the right order. In Cliff Shull's case he almost never ended up practicing science, let alone atomic physics. Early in his childhood he wanted to become an artist like his older brother, Perry Leo Shull. In fact, one can see this talent in the neatness and exactness of the many drawings of equipment and experimental designs that appear in Cliff's notes, sketches, and log books.[4] When approaching a new problem, he would typically first draw a picture laying out the problem. I have also come to understand this talent was a point of personal amusement later in his career when he found his students having difficulty making 3-D sketches of objects.[2]

FAMILY, INTERESTS, AND LIFE PHILOSOPHY

My father, Clifford Glenwood Shull, was born on September 23, 1915, to David Hiram and Daisy Ilma Bistline Shull. He was the youngest of three children, Evalyn May being the oldest, and his middle name was the section in Pittsburgh, Pennsylvania, where his family lived at the time of his birth. His brother, Perry, was named after the farming county in central Pennsylvania (northwest of Hartford) where their father had been raised. Cliff obtained his strong sense of humor from his father, who owned a hardware and home repair business. I remember my father once describing a family trip back to Perry County when, after arriving late at night, they pitched a tent in front of the house of Cliff's uncle in order to teasingly anger the uncle upon his waking up in the morning and finding strangers camped on his property. Throughout his life Cliff would love a good practical joke; one of his favorite Boston establishments was Joe's Joke Shop, where we would obtain things like fake vomit, rubber snakes, and plastic spiders for use in tricking other family members and friends.

Cliff's father and mother were both frugal, and this trait was picked up by Cliff at an early age. From his father's hardware store Cliff also learned to build things and to figure out how things worked. Consequently, in the future when one visited his MIT laboratory, it wasn't uncommon to find Cliff on his back fixing a spectrometer or rebuilding the shielding bricks around his experiments. He also had a woodworking shop at home that he used extensively for home projects like specially designed shelving, sturdy (but rough) furniture, a support system for an extensive two-tier model railroad set, and a hoist and elevated storage system for a 4 m (13 ft) motor boat. His childhood was comfortable but thrifty. The one extravagance was traveling on weekends to different communities where his father harness-raced sulkies. During these formative years, flying paper airplanes and redesigning them to do acrobatics also turned into a special interest in aeronautical engineering.

An important turning point in Cliff's career came when he decided to attend Schenley High School, a 45 minute commute by trolley and bus, rather than the local community school because of its better scholastics. At this high school he took a physics course taught by an unusual teacher, Paul Dysart. He was unusual in the respect that he had a Ph.D. degree. Because of his advanced education he knew his topic well and loved the area. Combined with his knack of exciting students with experiments and his clear explanations, Dysart captured Cliff's interest and directed him toward the physical sciences. Cliff excelled in high school, and due to Dysart's mentorship began to think about the possibility of attending college. Cliff's older brother, an art student at Pennsylvania State University, even acted as a role model. A half-tuition scholarship to the local university, Carnegie Institute of Technology (now Carnegie Mellon University), pretty much cemented that thought, since Cliff's family could now afford it with Cliff living at home. In the fall of 1933 Cliff entered the Carnegie Tech freshman class.

While at Carnegie Tech, Cliff began to seriously consider physics as a future career direction. Partially this was due to a freshman physics course given by the head of the physics department, Harry Hower.[3] Due to the fact that his classes were always entertaining and inspiring, they became some of the must-attend classes of the freshman class. During his junior and senior years, Cliff also worked to earn spending money during the summers in the laboratory of Emerson Pugh, one of the foremost authorities of the Hall effect at that time. This laboratory experience and the close relationship he formed with Pugh, combined with his almost straight A undergraduate record (metalworking laboratory being the singular exception), culminated in Cliff's decision to continue his physics education into graduate school. Emerson Pugh suggested he look at New York University for this graduate work, as it was one of the largest universities in the United States at that time. A very positive letter of reference[5] from Emerson Pugh to NYU surely helped assure Cliff's admission in the fall of 1937. Perhaps an additional reason Cliff chose to join the NYU Physics Department was the fact that a previous department chairman, Richard Cox, had increased the stipend for teaching assistants to $1,000 a year when the going rate was only $300 elsewhere.[6]

Graduate work at NYU turned out to be the perfect place for Cliff.[7] At that time the New York area was a center of atomic physics. Albert Einstein was at Princeton University, Enrico Fermi had immigrated to the United States and had a group working on nuclear fission at Columbia University, Isidor Rabi was conducting molecular beam experiments determining nuclear magnetic moments also at Columbia University, and there was a nucleus of professors (Allan Mitchell, Richard T. Cox, Frank E. Myers, Martin D. Whitaker, Robert D. Huntoon, William Crew, Norman Hilberry, Otto Halpern, Montgomery Johnson, and later Yardley Beers) at NYU working in the area. In addition, a weekly seminar organized by Otto Halpern at NYU brought the students into contact with this local community.

While at NYU, Craig Crenshaw, one of Cliff's fellow graduate students, arranged a blind date for Cliff through Craig's girlfriend at that time at Columbia University. That blind date, who subsequently became Cliff's wife, was Martha Nuel Summer. She was an only child from a moderately well-off family in Newberry, South Carolina, who had left home to attend college at Randolph Macon Women's College in Lynchburg, Virginia. After obtaining a bachelor's degree in history, she decided to attend graduate school for an advanced degree, an unusual thing at that time for a "southern lady," especially at a university so far from home. It was after she had obtained a master's degree in history at Columbia University and was working toward her Ph.D. that she met Cliff. Interestingly, her birth date was September 25, 1915, only two days after Cliff's. Also interesting was the fact that the rooming house in which she lived was also shared by an Italian refugee, Bruno Pontecorvo and his family. Pontecorvo—with Emilio Segrè and Franco Rasetti—was part of the Enrico Fermi group at the University of Rome prior to Fermi's immigration to the United States; Pontecorvo had left Italy in 1933 but rejoined Fermi at Columbia University. Since they shared a kitchen, Martha became friends with Pontecorvo's wife, Maryanne, especially since they both spoke German and Maryanne did not speak English. Through this acquaintance Cliff also was introduced to them and heard of Fermi's activity at Columbia.

As Cliff was finishing up his thesis work in the spring of 1941 he and Martha took a trip to South Carolina. Knowing that he would be receiving his Ph.D. degree later that year and would have enough money to support a family at his new job working for the Texas Company (the forerunner to Texaco) in Beacon, New York, Cliff proposed marriage to Martha during this trip. As Martha had not yet finished writing her Ph.D. thesis, I suspect that Cliff was not certain what her answer would be. At any rate Martha accepted and they were married in Martha's home town about four months later, in June 1941, shortly after Cliff received his Ph.D. degree.

Martha was a perfect partner for Cliff. They were equals intellectually, but where Cliff was methodical, Martha was impetuous; where Cliff was quiet, Martha was a keen conversationalist; where Cliff was mathematical, Martha was philosophical; and where Cliff was nonconfrontational, Martha could be insistent. As a consequence Martha's strengths complemented Cliff's, thereby making it easier for him to meet with others, while also making certain others did not take advantage of Cliff and Martha's pleasant dispositions. Martha also handled most of the home duties, thereby enabling Cliff to focus as he developed his particular brand of science unencumbered by many distractions. The match was the beginning of a real-life love story that didn't end until their deaths two days apart in 2001 when Cliff saw how terribly Martha's health had deteriorated and gave up his own will to live.

From those early days in Beacon, New York, Cliff recognized there was more to life than physics and made certain he also devoted time to his wife and later family. Favorite interests of theirs included hiking and camping trips in the Adirondack and White Mountains. Since the United States joined the Second World War later their first year together, they both learned to conserve, working together to can fruits and vegetables, reuse things, and make things they needed. This attitude remained with them for the rest of their lives. Their first son, John Clarence, was born in November 1944, not long before the end of the war. Two years later, in Oak Ridge, Tennessee, their second son, Robert David, was born and three years later their third son, William Francis, joined the family. While in Tennessee, Martha joined and became very active in the American Association of University Women and organized many events for them, including a visit by Eleanor Roosevelt. Martha felt women were unfairly directed into only certain career paths and the way out of that dilemma was higher education for women. She used the AAUW as a vehicle to educate others to the excitement of various occupational choices and stayed active in this association well after she and Cliff left Oak Ridge.

Martha was very much the extrovert in the family, and through her activities many strong professional and social friendships were formed during those years at Oak Ridge and later. She was an expert in the art of small talk, and immediately set people at ease with her southern accent at professional meetings or at parties she and Cliff would host at their home. Interestingly, she never lost that accent, despite living in the "north" for 46 years after leaving Tennessee. Martha's easy way with people also taught Cliff those attributes, and that enabled him to easily meet people, especially other eminent scientists.

The annual family vacation to the beach or mountains was always a high spot for the family. I remember one particularly great outing where my two brothers and I backpacked with our father for three days in the Great Smoky Mountains, successfully evading the many black bears in the area, sleeping at rustic campsites and being picked up by my mother at the side of a road many miles away from where we had started. Another passion of Cliff's was classical music. Consequently, most evenings were spent with the radio playing in the background tuned to a station playing Beethoven's *Pastoral* or *Eroica* symphonies, Tchaikovsky's First Piano Concerto, Rimsky Korsakov's *Scheherazade*, or other such piece. While this was occurring, Cliff would be working on some problem at his desk in the living room or using an old adding machine repetitively pulling the manual handle to add up numbers (neutron intensity data) printed out on a long roll of paper tape. At other times Cliff would be using a Leroy lettering set and French curve on the dining room table to draft a figure for publication. Weekends were spent together as a family gardening, working on some construction project, exploring the woods adjacent to the property in Tennessee or Massachusetts, or playing with the English setter puppy Cliff added to the family in the early 1950s. Once the family moved to Lexington, Massachusetts, much time was spent digging out huge boulders from the lawn, constructing a rock wall around the family property, making flower gardens for Martha, and exploring the local woods.

While the kids were growing up, Cliff intentionally refrained from pushing science on them, despite what, I'm sure, was his wish that they would choose that as a career path. However, he was supportive in whatever career was ultimately chosen. During annual vacations visiting the grandparents in South Carolina or Pittsburgh, camping in the White Mountains, or renting a cabin on the edge of

Lake Monomonac in southern New Hampshire, science was not usually a topic of discussion. However, Cliff would teach us that science was all around us as he explained "why this happened" or "how that works."

At times Cliff would take risks, but they were always calculated risks. As, for example, when at age 45 Cliff took up water skiing along with the rest of the family, and three years later took up snow skiing. After that it would not be uncommon to find the male members of the family during winter weekends slaloming down some new ski trail in Vermont or New Hampshire. On occasion a student or visiting scientist at MIT would also join the group on the slopes, and thereby set a good example for my brothers and me.

Despite not pushing physics, Cliff still made certain we were exposed to it by occasional trips to his office and seeing him work at home. There was also always the unmentioned expectation that his children would attend college after high school. Therefore, it was not until I was an undergraduate at MIT that I really found out what my father had accomplished. And, I recall, that first occasion was not particularly instructive. As a freshman, one day I attended a seminar he presented to the MIT Physics Department. Unfortunately, I had stayed awake the whole previous night working on a humanities paper, and promptly fell asleep when Cliff turned out the lights in his seminar to show a few pictures. When I saw him the next day, in his typical humor all he said about the previous day's incident was that he hoped I didn't always try to "learn through the noise of my own snoring." He then pointed out that the other people in the audience "didn't seem to think it was that boring." I learned more about Cliff's work at a subsequent physics department lecture by him a couple years later when my eyes remained open.

Cliff really enjoyed teaching. Perhaps it was because he remembered what an important influence his high school teacher, Paul Dysart, had been to him. I think it was that Cliff got a great thrill out of learning the wonders of Nature and wanted others to share in that experience. A colleague, Herb Bernstein, remarked that Cliff's science was not about getting the answer; it was about understanding why the experiment sometimes did not give the "right" answers.[8] As Marc Kastner, MIT Physics Department chairman in 2001, would relate at Cliff's funeral,

> I remember as a young assistant professor sitting in my office one day and Cliff came charging into my office with a graph of a new measurement he had made. He was just extremely excited; he had discovered some new magnetism in a material in a way that he had never thought was possible. It wasn't an earth shaking discovery; it wasn't of the scale of things he had done before. But it was something new and interesting, and Cliff was genuinely excited about it. That joy in learning about Nature was something he communicated to everyone, particularly to graduate students, and that enabled him to educate some of the great physicists of our time. When Cliff took over the MIT Junior Physics Laboratory, a course most physics undergraduates dread because it takes 24 hours/day, Cliff invented new experiments for the students to do, like neutron scattering experiments at the MIT reactor, or superconductivity experiments at MIT's National Magnet Laboratory, that made it all fun as Cliff communicated to them the joy of learning about nature.[8]

By example Cliff also tried to teach his students that science was not always following the rules set by others before you; instead, it was the wonder of experimenting in new areas and of describing the observations in your own way.[9]

PHYSICS

In 1928 Richard Cox and his colleagues at Johns Hopkins University made an unsuccessful attempt to determine whether free electrons were polarized. This interest in the polarization of electrons continued after Cox joined the Physics Department at NYU, which was located in the upper Bronx section of New York City at the University Heights campus, rather than at the main campus in Washington Square, Manhattan. In 1930 Cox obtained grant money with Robert Huntoon and a new faculty member, Frank Myers, to construct a 200 keV Cockroft-Walton generator/accelerator for nuclear reaction studies. This generator was nearing completion when Cliff arrived as a graduate student at NYU, and Cliff joined the project as a student of Frank Myers to study deuteron-deuteron interactions. Two years later Cliff began his Ph.D. thesis work by starting construction of a more powerful 400 keV generator of the type invented only eight years earlier by Robert Van de Graaff at Princeton University. His focus would be to use the greater flux of electrons from this device to revisit the electron polarization question. After a year of construction, bending many aluminum tubes and scrounging equipment in this low-cost project,[10] Cliff was nearing completion of the accelerator when Frank Myers left in 1940 on sabbatical to work with its inventor, now at MIT. Richard Cox took over as Cliff's thesis adviser for the next year, and it was during this time that Cliff solved several problems associated with the operation of the generator and used it to perform a double scattering experiment of electrons by very thin foils of gold.[11] These experiments first displayed the ingenuity that was to distinguish Cliff in the future as an experimentalist *par excellence*. The experiment was designed to have good statistics due to the high flux of electrons from the Van de Graaff generator: thin foils were used so only single scattering events were possible; scattering events from the optimal material, gold, were investigated; simultaneous measurements were performed to either eliminate or enable the separation of background effects; and several related experiments were conducted in order to provide unequivocal conclusions (1943). The work clearly demonstrated for the first time that an electron beam does have a net spin and could be polarized differently by reflection and transmission, as theoretically predicted. It has been suggested that these and the earlier experiments by Cox may have actually been the first demonstrations that parity in physical processes is not conserved,[12] a notion that waited 15 more years to be announced.[13]

Cliff also benefitted during his time at NYU from association with several fellow graduate students, who subsequently had distinguished careers in nuclear physics. These included Craig Crenshaw (his best friend), Carl Chase and Bowen Dees (students of Richard Cox), William Bright (a graduate student of Martin Whitaker), Morton Hamermesh (a student of Otto Halpern), Wilber Spatz, John Simpson, and Henry ("Hank") Manning. Many of these students would regularly meet in Dees's apartment since he had a larger place due to his being the only married graduate student at the time and discuss seminars, physics, problems, and successes. According to Dees,[6] Cliff was generally regarded as one of the brightest of the bunch. Through these "club" meetings and the lecture series organized by Halpern, Cliff was to learn about the other research activities going on in the department. Included in this activity was the work of Martin Whitaker using his low-intensity radium-beryllium neutron source to probe nuclear reactions and the theoretical work of Halpern and Johnson on neutron interactions with paramagnetic materials. Cliff would recall later in his career what he had learned during this period when he began focusing on neutron scattering. It was also during this period that Cliff developed his trademark work ethic of spending long hours in the laboratory and patience in measurement. Due to heavy teaching responsibilities Cliff's only opportunity for operating the accelerators he was building was during weekends. He and the other graduate students would typically start these devices on Friday afternoon and work straight through to Saturday night, improving on them or collecting data. On Sundays, they recuperated.[14]

The year 1941 turned out to be hectic for Cliff. He finished his Ph.D. work and proposed to Martha in the spring, obtained his Ph.D. degree in June, got married at the end of that month, and moved to Beacon, New York, to begin work at the Texas Company in July. At the Texas Company he became involved in the development of improved catalysts. These were needed in the Second World War, which the United States entered at the end of 1941, for the production of high-performance aviation fuel needed by the bigger and more powerful jet engines being engineered at the time. After being introduced to the area of X-ray scattering in this job, Cliff soon excelled in it as he extended the theories of W. H. Bragg, P. Scherrer, F. W. Jones, and others to calculate the true diffraction line widths in binary mixtures of materials as a function of the relative crystal sizes.[15] Subsequently, with L. C. Roess he developed the theory for X-ray scattering at small angles by small particles, extending the theory of A. Guinier, and developed an exact theory for the small angle X-ray scattering by a continuous distribution of spheroidal particles of different shapes ranging from discs to rods (1947). Because of the importance of the neutron scattering technique, which Cliff pioneered later in his career, this work at the Texas Company has generally been missed by the larger scientific body. However, its impact has been significant. These results are widely used today by the small-angle scatterers to analyze their data not only in the X-ray community but also in the neutron and electron scattering communities. This activity of Cliff's also brought him into contact with many of the preeminent X-ray scattering leaders of the time, such as Bertram Warren, Martin J. Buerger, Isidor Fankuchen, William Zachariasen, Paul Ewald, David Harker, Newell S. Gingrich, and J. D. H. Donnay.

One major disappointment in Clifford Shull's life occurred in the period between 1942 and 1944. As the United States became more involved in World War II, and the Manhattan Project got underway in Chicago, many of Cliff's previous professors (Frank Myers, Martin Whitaker, William Crew, and Norman Hilberry) and fellow students (John Simpson and Wilber Spatz) from NYU left New York City to join the effort in the Windy City. Shortly thereafter in 1942 Cliff was invited to visit the project. During the visit, he was informed in very general terms what was going on at this facility. He became very excited by the research occurring there, and was invited to join the effort. Upon his return to New York, Cliff told Martha to "start packing her bags"[16] since he was accepting a job offer he had just received in Chicago. When Cliff told the Texas Company he wanted to change jobs, the company was not pleased at the prospect of losing him, especially when Cliff could not tell them what it was he would be working on. Due to the war, at this time people could not change jobs at will; one could only change positions if the new job had a higher war effort priority. A decision forbidding Cliff to leave the Texas Company was ultimately decided by a War Manpower Court, but that did not occur until near the end of 1944 as the war was drawing to a close. Through the perspective of 20/20 hindsight, it was probably fortunate Cliff had not been allowed to join the Manhattan Project. The time at the Texas Company had enabled Cliff the opportunity to learn X-ray scattering from crystals so well that he ended up developing new scattering science. If he had left the Texas Company early, he might not have become so proficient in scattering phenomena to appreciate the deviations presented by the scattering of neutrons, and may not even have become interested in the scattering of neutrons.

By the time the war ended in August 1945 many of Cliff's friends from the Chicago project had moved to the operation at Oak Ridge, Tennessee. One of those friends was Martin Whitaker, the former NYU professor who had been investigating neutron polarization effects by interaction of neutrons with magnetic materials (using his low-intensity radium-beryllium source). Whitaker was now the head of the research laboratory at Oak Ridge, then called the Clinton Laboratory and later the Oak Ridge National Laboratory. At this site a nuclear reactor had been constructed, called the Clinton Pile (and later the Oak Ridge Graphite Reactor) for providing material property information needed for the war effort. A spectrometer had been added by Ernest O. Wollan, a former student of the 1927 Nobel laureate Arthur Compton (known for his incoherent X-ray scattering work) for measuring coherent neutron scattering characteristics of various atoms. Still interested in joining the excitement that he had glimpsed during his wartime visit to the Metallurgical Laboratory in Chicago, Cliff contacted his friends in Oak Ridge, and in February 1946 Whitaker invited Cliff to visit. During that visit, which occurred in April, Wollan showed Cliff the neutron scattering data he and R. B. Sawyer had recently obtained on a pressed pellet of NaCl powder showing several diffraction peaks. The monochromatic beam used for these experiments had been obtained by diffracting the multi-energetic neutron beam out of the reactor from an NaCl single crystal. Wollan had thought powder samples should be optimal since he had earlier been plagued by irreproducible results on single crystal samples, possibly caused by extinction effects. Cliff became very excited by these powder patterns as well as diffraction data observed by Wollan and Sawyer for liquid samples of H_2O and D_2O. Since Cliff was no longer bound by the war manpower restrictions, when Whitaker offered him a position at the Clinton Laboratory, he accepted it. Two months later Cliff moved to Oak Ridge with a pregnant wife and their 19-month-old son, John C. Shull. Five months after that their second child, Robert D. Shull, was born. So Cliff was starting out his new career with the added responsibility of having to devote time to the care and upbringing of two young children who did not care that their father needed "thinking time" when at home.

The first diffraction lines for the NaCl powder measured by Wollan and Sawyer had magnitudes above the background about equal to the background intensities. Consequently, one of the first priorities upon Cliff's joining the group at Oak Ridge was to understand and reduce the background scattering. It took Cliff over a year to track down the major sources. In addition to instrumental effects due to insufficient source and detector shielding, a large contribution was from diffuse scattering by the samples, much larger than predicted by theory. It was also found that the coherent scattering cross-sections Cliff and Ernie Wollan were measuring were not consistent with the total scattering cross-sections determined from transmission experiments. One of the sources of the diffuse scattering was thought to be from nuclear spin incoherence. Cliff and Ernie Wollan finally settled this question when they measured the scattering from a monoisotopic atom with no spin, carbon, in its three forms: diamond, graphite, and charcoal. All three showed large amounts of diffuse scattering when neither spin nor compositional variations could be blamed. Cliff and Ernie realized the diffuse scattering was coming from multiple scattering effects within the crystals when they calculated the magnitude of those effects for diamond and found consistency with the total scattering cross-section for carbon (1948,1). Cliff explained later: "I have asked myself why the solution was so long in coming. The answer lies in the fact that this effect was foreign to both Ernie's and my earlier x-ray diffraction experience, although I had encountered multiple scattering of electron beams in my earlier graduate thesis work."[17]

With this breakthrough Cliff and Ernie could now interpret the neutron intensities with confidence. In the next three years they measured the scattering from over 100 different elements and compounds and determined the coherent and total nuclear cross-sections and the neutron scattering factors for over 60 elements and isotopes (1951,1). That feat is almost monumental when one realizes how much angular data is required for such determinations for each material and in light of the fact that each angle in the earliest spectrometer needed to be positioned by hand and counting needed to be performed for long periods of time to obtain good statistics. As Cliff recalled in 1994: "It was very exciting for us because almost everything that we touched, every type of problem we tackled, showed up with new facets and the potential (for neutron scattering) became apparent in those early years."[1]

During this flurry of activity, several other discoveries were also made. From studies on NaH and NaD powders Cliff and coworkers showed both hydrogen (H) and deuterium (D, heavy hydrogen) scattered neutrons but with oppositely signed amplitudes and determined the scattering amplitudes for both ortho- and para-hydrogen proton spin states (1948,2). For the first time there was now a probe that could determine the positions of elements as light as hydrogen in various structures. The first Laue photograph,[18] the first neutron radiograph,[18] and in α-Fe_2O_3 the first spin reorientation effect was discovered using neutrons (1951, 3). In addition, Cliff and Ernie measured the diffraction from powdered D_2O and H_2O ice crystals, which solved the controversy over four prevalent crystallographic models of the water molecule in favor of the "half hydrogen" structure model of L. Pauling (1949,1). In honor of this latter achievement, many years later in the 1970s, a feature in the Crystal Sound in Antarctica was named after Cliff: Shull Rocks (66°27'0"south, 66°39'58" west). Similarly, there were other features in the same vicinity named after other notable scientists for their significant scientific achievements related to water and ice, such as Pauling, Bernal, and Weertman Islands. When informed of this honor in 1996, Cliff exhibiting his typical humor quipped, "Perhaps there is a hidden message here with my only getting some rocks while others were getting islands."[16]

During the time Cliff was at NYU, professors O. Halpern and M. Johnson theoretically calculated details of the magnetic interaction of neutrons with magnetic spins in a material. Attempts by Martin Whitaker to verify those calculations while Cliff was at NYU were unfortunately hampered by the low intensity of neutrons available to him in those days. Cliff was very familiar with that theoretical activity, especially since he was such close friends with their students Mort Hamermesh and William Bright, respectively. In addition, Cliff possessed a phenomenal memory. (I remember in later years Cliff being able to immediately cite the date, authorship, and work he had read about many years before, even in areas in which he was personally not working.) Consequently, in his quest to determine the coherent scattering cross-sections for neutrons in a multitude of materials, several of these materials were selected in order to investigate the scattering by magnetic spins in those crystals. Unlike nuclear scattering factors, magnetic scattering factors varied with the scattering angle, as first deduced by Cliff from his diffraction data. This provided a way to separate the two contributions to any diffraction peak, thereby enabling the magnetic character of the material to be independently probed. As a consequence, Cliff verified some of the earlier predictions of Halpern and

Johnson (1951,3) and opened up the technique for probing magnetic structure.

One of the first truly breakthrough discoveries in this latter regard occurred in 1949. L. Maxwell and J. Samuel Smart, from the Naval Ordnance Laboratory in White Oak, Maryland, informed Cliff of theoretical predictions by Louis Néel in France of the possible existence in materials, especially oxides, of a novel ordered magnetic state, called antiferromagnetism, wherein adjacent atomic magnetic spins were aligned antiparallel to each other. Cliff realized this phenomenon could explain an extra low-intensity diffraction peak he had measured earlier in α-Fe_2O_3, one of the possibly antiferromagnetic materials suggested by Néel. In addition, Cliff recalled having measured a large amount of diffuse magnetic scattering at room temperature in another weakly magnetic oxide, MnO. Cliff was suspicious that the diffuse scattering suggested local short-range ordering of magnetic spins that might then develop long-range magnetic order at lower temperatures. With J. S. Smart, Cliff subsequently published the first proof of Néel's predictions, using neutron scattering data from α-Fe_2O_3 and MnO (1949,2) that caused an immediate excited reaction in the scientific community.

At the 40th Annual Magnetism and Magnetic Materials Conference in 1995, a personal friend of Cliff's, Jack Goldman (a previous director of Ford Motor Company's Scientific Research Laboratory who later became the founder and director of Xerox's PARC laboratory), recalled the excitement in 1949 of hand carrying to Louis Néel in France a rough graph of Cliff's new data.[19] The data showed an apparent doubling of the (111) lattice constants at 80 K compared with the room temperature results, thereby indicating the presence of alternating spin scattering on adjacent (111) planes at low temperatures and proving that antiferromagnetic ordering exists. In the magnetism community this was a truly startling discovery that opened up the possibility of other types of magnetic ordering. The study also established neutron diffraction as a key technique for magnetic structure resolution. Shortly thereafter, Cliff published a couple of major reviews of the magnetic scattering of neutrons (1951,3,4). This time must have been a particularly hectic time for Cliff since he also had added responsibilities at home with his third son, William F. Shull, being born also during this period.

An important secondary discovery was also made by Cliff at the same time he was testing Néel's antiferromagnetism predictions. While measuring the neutron scattering from Fe_3O_4 powders, Cliff found that one of its reflections, the (111) plane reflection, was almost completely magnetic in character. He recognized that this reflection could be used to settle a long existing controversy over whether the neutron should be considered a point dipole (as suggested by F. Bloch in 1936) or an amperian current (as suggested by J. S. Schwinger in 1937). Since Fe_3O_4 is ferromagnetic at room temperature, its magnetization direction can be changed by varying the direction of an external magnetic field, thereby changing the angle, α, between the magnetization direction and the scattering vector of the (111) reflection. The $\sin^2\alpha$ variation in intensity measured by Cliff clearly supported this prediction of the Schwinger model over the $\cos^2\alpha$ dependence expected if the Bloch model were correct, thereby unequivocally proving the correctness of the amperian current description for the neutron (1951,3). Again, the simplicity in the experimental design set Cliff apart from his peers. This experiment is also an example of another one of Cliff's trademarks: cognizant about how to apply results in one area to solve important questions in other areas. In this case it resulted in an advance of the scientific community's fundamental understanding of the neutron.

During the Fe_3O_4 powder investigation, another important discovery was made. Cliff found that the (220) reflection was composed of almost equal magnetic and nuclear contributions. He recognized that according to the theory of Halpern and Johnson, this reflection from a single crystal could then be used as an effective way to obtain a highly polarized neutron beam (1951,2). Up to this time, polarized beams had only been made by resonance experiments, mirror reflection, or transmission through a ferromagnet. This new method had the particular advantage that in a single diffraction event one could obtain a beam that was both monochromatic and polarized. Despite the fact that he could not test this idea for another four years, until he obtained a single crystal of Fe_3O_4 from Arthur von Hippel at the Massachusetts Institute of Technology, Cliff tried the same experiment using the less perfect (110) reflection from pure Fe with partial success.

For the next four to five years Cliff and his Oak Ridge colleagues, most notably Mike Wilkinson, focused on the magnetic scattering of neutrons in a number of materials, including the transition metals and their alloys, rare earth oxides and metals, and perovskite compounds. He discovered unusual types of antiferromagnetism in chromium and manganese,[20] developed methods for analyzing the diffuse magnetic scattering to determine atomic magnetic moments,[21] and presented strong evidence that the atomic moment of the transition elements is a function of the local atomic environment in their alloys.[22] In 1956 Cliff received the Buckley Prize from the American Physical Society for his use of neutron probes to elucidate the magnetic structure of materials.

Despite the success of Cliff's scattering results and associated theories he developed for extracting the most from every experiment,[23] not everyone was quite so willing to accept the results of his new techniques. In June 1952 at the American Crystallographic Association meeting in Tamiment, Pennsylvania, Cliff gave an invited talk on his neutron scattering work that had enabled his locating the positions of hydrogen atoms in various crystal lattices, including those of zirconium and thorium. In that talk he showed that when the very broad maxima in his measured data are analyzed by taking into account the presence of multiple scattering processes occurring in the material, the neutron scattering data could be used to position very light atoms, like hydrogen. Afterward the eminent scientist Peter Debye (1936 Nobel laureate in chemistry) remarked, "Young man, your data are fuzzy, your mathematics should (also) be fuzzy!"[24] An opposite reception by the scientific community was related by Laszlo Tisza (previous student of Werner Heisenberg) when Cliff Shull traveled to MIT in the same time period and delivered a lecture on his new methods of investigation, with a visiting Max von Laue (1914 Nobel laureate in physics for X-ray scattering theory) in the audience. After Cliff's talk, in which he probably showed the first Laue patterns obtained from neutron scattering, von Laue's response was simply to come up to Cliff and give him a big hug.[25] Such drama was not lost in that audience, which also included Bertram Warren, Isidor Fankuchen, and John C. Slater.

In 1955 Cliff succumbed to overtures extended to him by John Slater, an eminent theorist at MIT, to leave Oak Ridge for a professorship in the Physics Department of MIT. The fact that MIT was willing (at the insistence of Martha) to give Cliff an immediate full professorship without his having done any previous teaching attests to how high a regard they must have had for him. Cliff accepted this offer because he would have access to a 5 MW research reactor that MIT was beginning to construct on the campus. In addition, the move would enable him closer interaction with theorists such as Slater and his students, and the opportunity afforded Cliff the prospect of teaching and working with bright graduate students. However, since it would take about two years to finish construction of the reactor, Cliff arranged with MIT for him to spend much of that intervening period conducting neutron scattering investigations at the Brookhaven National Laboratory.

Upon arriving at Brookhaven, Cliff convinced the local scientists to reconstruct an older spectrometer to become a dedicated polarized beam setup, taking advantage of the Fe_3O_4 single crystal he had just obtained.[26] Such experimental capability was important in order to definitively determine the magnetic spin directions in a material, using the theories developed by Halpern and Johnson almost 20 years earlier.[27] It also enables an easier separation of the magnetic and nuclear scattering intensities in any specific diffraction peak. The Fe_3O_4 crystal verified the expected near 100 percent neutron beam polarization from the (220) reflection. In the summer of 1956 Cliff also spent a couple months as a consultant to Bell Laboratories scientists interested in neutron scattering and obtained a single crystal of Co-8%Fe from Richard ("Rick") Bozorth, a noted expert in ferromagnetism. Cliff had recognized from his earlier work on Fe-Co alloys that as Co is added to Fe, the magnetic scattering factor increased while the nuclear scattering decreased, suggesting to him that one would have near equal scattering at 8%Fe in Co and therefore complete polarization of a neutron beam. At the same time the overall scattering would be increased when compared with that from Fe_3O_4, due to the metallic nature of the Fe-Co alloy. It was subsequently found that the polarization of the neutrons diffracted from the Co-8%Fe crystal was opposite to that obtained after diffraction from the Fe_3O_4 crystal; Cliff and Robert Nathans used this relationship to great advantage by alternating these two crystals to obtain alternating polarizations. They had realized one could obtain significantly improved precision in the determination of magnetic scattering factors by measuring the diffracted intensity for opposite polarizations and using the ratio of those scattered intensities to determine a "flipping ratio" (1959). In particular, this method enables one to sensitively detect the smaller magnetic scattering in the presence of much larger nuclear scattering. Again the simplicity of the experiment has resulted in its now being a common method used throughout the world since Cliff's early development of methods for providing polarized beams.

Arne Andresen, a visiting scientist at Brookhaven National Laboratory at the time, remarked[28] how one weekend Cliff showed up at the BNL with an rf oscillator power supply he had scrounged that week while at MIT with a new idea for reversing the neutron beam polarization, patterned after a discovery by I. I. Rabi. In short order they found that for an 8-cm-long coil they only needed to create a field of 7.96 kA/m (100 Oe) at a resonance frequency of 287 kHz to accomplish this reversal on a beam of neutrons flowing through the coil. Such rf systems are now commonplace since the field in the coil can be turned on and off to flip the polarized beam very quickly. Cliff and others at BNL used this technique to first determine the spin density distribution in Fe and Ni, and then the polarization of diffracted neutrons from antiferromagnetic Cr_2O_3.[29]

During the reconstruction of the spectrometer at Brookhaven into a polarized beam system, there were constraints on where the polarizing devices could be placed. As a consequence, the spectrometer was constructed so that it bent the neutron beam to the left. This was not thought to be important, but it was apparently to be one of the few such systems in the world configured that way. That rotation choice would turn out to be fortuitous much later when Cliff would recall this difference in tracing down a disturbing discrepancy in the data measured on the BNL system in comparison with that measured in a right-handed system constructed at MIT (1963).[26]

It was also during this two-year period living on Long Island that Cliff acquired a long-lasting interest in water sports, starting with sailing. Together with Robert Nathans he purchased a 4 m (13 ft) sailboat in dire need of repairs. After spending many hours sanding, recaulking, and repainting the boat, it was ready for launching. As Cliff related in a letter to John Slater at the time,[30] the "ship," which they had renamed *Slow Neutron*, stayed above water for 20 feet before it sank to the bottom. In his typical scientific manner Cliff related how that event was not unexpected, and that the sinking was precalculated to be required in order to swell the caulking and seal the boat. My personal view was that it was an afterthought. However, their "pre-calculations" did prove to be correct, and within a week, the *Slow Neutron* stayed afloat long enough (with constant bailing by the passengers) for trips with the family across the Long Island Sound out to Fire Island and back. Much later, in the early 1960s, Cliff and I would embark upon a project to build a sailboat using plans obtained from the classified advertisement section of the *New York Times*. That boat was constructed without requiring caulking and presinking. Between those two periods Cliff learned to water-ski and spent many annual family vacations skiing on a lake in New Hampshire behind a small 18 hp motorboat. Despite the small miscalculation in the minimum power needed to lift an adult above the waterline, Cliff persisted in experimenting until he was successful at doing it. Again, as in all of Cliff's experiments, patience and persistence were keys to finding the solution.

As soon as the MIT reactor was completed in 1956 Cliff set up an improved polarized beam spectrometer that was used extensively by a multitude of graduate students in Cliff's laboratory.[31] Much of the work during this time was focused on investigating the fundamental properties of the neutron and developing an understanding of the magnetic character of the ferromagnetic elements iron, nickel, and cobalt through Fourier inversions of the scattering data. They found surprising regions of negative magnetization in the Fe atom,[32] discovered a new type of interaction (the neutron spin/neutron orbit interaction [1963]), improved by over six orders of magnitude the upper limit for the electrical charge of the neutron (1967,1), and detected the electron polarization cloud of the conduction electrons around magnetic impurities predicted by the theory of the Kondo effect in Cu-Fe alloys. [33]The neutron spin-orbit interaction was deduced from the fact that the intensity of coherent Bragg scattering from a vanadium crystal[34] was neutron polarization dependent when no magnetic field was present. In keeping with Cliff's philosophy that one should never ignore inconsistent results and that one needed to account for even the smallest discrepancies in the data,[35] he recognized the neutron spin must sense the charge of the nucleus. He subsequently calculated the magnitude of such an effect and found that the calculated result was equal to that deduced from the vanadium data (1963). Interestingly, this new interaction would also suggest slightly different intensity measurements between left-handed and right-handed beam spectrometers, just of the same magnitude and direction as detected earlier using the BNL system. Another case solved.

Cliff operated under the philosophy that the free exchange of ideas was more important to good science than withholding information in the interest of competition. He would always make certain he credited others for their contributions. A good example of this ethical principal was related by Norman Ramsey, the 1989 Nobel laureate in physics.[36] In order to test for the possibility of time reversal invariance violations Cliff had devised a polarized-beam neutron scattering experiment to search for an electric dipole moment on the neutron, which would signal the violation. Up the street at Harvard University, Norman Ramsey was using resonance methods to search for the same thing. As the first person to find such a dipole moment would receive high acclaim, the competition was intense. Cliff entered into a gentleman's agreement with Norman that as soon as one of them was ready to go to press with their results, he would inform the other person and give him 24 hours to ready his own manuscript for back-to-back publication. Both groups finally published back-to-back in *Physical Review Letters* (1967,2).[37] Even though the results were negative, they both set a much lower limit to how large such a dipole could be if it did exist. To Cliff even the null experiment was interesting. His precept was, "Any new experiment is worth doing, even if current dogma holds it to be unnecessary. We don't know everything, and even if we did, we should give Nature the chance to surprise us from time to time!"[38]

The last 10 years of Cliff's work at MIT were devoted to examining the wave nature of the neutron, the diffraction of "imperfect" neutrons from "perfect" crystals (1973), and the examination of quantum mechanical effects of diffracting neutrons. The first Pendellösung fringes in neutron diffraction were observed (1968), the spherical-wave description of the neutron was proven to be superior to the commonly held plane-wave picture (1972), a smaller effective mass of the neutron was discovered in the crystal compared to vacuum (1980, 2), and a measurement of the Aharonov-Bohm effect for neutrons was first attempted (1981). Cliff always felt the particle-wave duality of elementary particles was unsettling. Consequently, he would design tests for the neutron in order to measure whether it would hold up to scrutiny as such a particle, just like the electron and photon. One such test was to determine if its wave nature could be substantiated, as by causing it to break up into constituent wave components during a Bragg diffraction event that would interfere with each other, thereby creating oscillations in intensity after transiting the crystal. Indeed, these oscillations, called Pendellösung fringes, were found (1968). Herbert Bernstein related how that discovery came just as Herb was finishing a lecture at BNL: "Cliff came running up with new data that he had just gotten from the reactor with Marty Blum and he was very excited; he had just seen the first evidence of neutron Pendellösung, which is really the switching back and forth between two different pendulums, and it was a kind of interference. He was trying to say way back in 1967 that someday there would be a way to do neutron interferometry."[8]

As in the past, when new insight had been obtained by Cliff, he would turn around and use that new understanding for other purposes. In the above case he recognized the spacing of the Pendellösung fringes could be used to determine structure factors to much higher precision than ever before. He subsequently measured the wavelength dependence of the locations of these fringes and determined very accurately the crystal structure factors for silicon (1972) and germanium,[39] from which he was able to obtain accurate values for their nuclear scattering factors. Cliff then recognized that he could obtain for the first time a good experimental value for the small nuclear charge scattering that arises because of the interaction between the charge distribution within the atom and both the neutron magnetic moment and neutron intrinsic charge structure (1973).

Such an interaction is very small, and the uncertainties in the values available in 1973 for the effect were comparable with the values themselves. Cliff's subsequent experiments and analysis resulted in far better measurements where the uncertainty was reduced to about 20 percent or so of the measured value, thereby for the first time giving confidence in the magnitudes for the effect. As a consequence of his pioneering work in neutron scattering, Cliff was elected to membership in the National Academy of Science in 1975. In a letter to me upon the announcement of this honor he stated, "That is about as far as a physicist can go!" Little did he know that he would surpass that honor 19 years later.

During his entire time at MIT, Cliff shared a large room with his students and visiting scientists in the building housing the reactor. In this environment it was common to have daily discussions, many of which started out with the words "what if."[40] In this way many people contributed to the generation of the many good ideas that came out of this laboratory. In these discussions Cliff insisted on "not using terms whose meaning is not clearly understood."[41] In addition, before new directions were pursued, rough calculations were always performed to make certain the expected magnitudes of the effects were measurable. Cliff was also not embarrassed to say "I wish I had thought of that" when a student came up with a particularly nice solution to a problem, thereby giving the student confidence in his own creativity.[9] Unusual in this close professor-student environment was the fact that Cliff always had an experiment of his own that he would be running either by himself or with a visiting scientist in parallel with those experiments of his students.[35] That way he felt more good science could be developed. Examples of those individual projects include the search for the electric dipole moment of the neutron (1967,2), the search for Pendellösung fringes (1968), and a single slit neutron diffraction experiment to check on whether a Fraunhofer pattern would be observed (1969). From the widths of the peaks in the Fraunhofer pattern he subsequently observed in this latter test, Cliff realized he could also determine the size of the neutron de Broglie wave packet (1973).

Seeing the power of interference effects at providing fundamental information about the neutron and its interactions, Cliff began construction of a neutron interferometer in 1976. Such a device had been developed earlier by Helmut Rauch (as well as another being developed by Samuel Werner) using three crystals,[42] but Cliff and his colleagues felt a two-crystal design would be more sensitive to the diffraction processes inside the crystals and would be simpler to analyze. With students Don Atwood and John Arthur along with visiting scientists Anton Zeilinger and Michael Horne a successful system was built.[43] As in all of Cliff's experiments the system was first checked out by making certain all intensities were properly accounted for by comparing the measured data with that calculated. In so doing, Cliff's group even accounted for new asymmetries they found in the intensities of the two exiting beams measured as a function of detector position parallel to the surface of the second crystal. Using this knowledge, they were then able to calculate with confidence interferometric effects. One of the first uses was to test for nonlinearities in the traveling-wave solutions to the Schrödinger equation (1980,3). Their null result reduced by three orders of magnitude the upper limit on the value of any such nonlinear term compared with that determined by Lamb-shift experiments.

The interferometer was subsequently used to further test the quantum mechanical properties of the neutron by searching for a neutron Aharonov-Bohm effect (1981). This effect is theoretically only supposed to occur for charged particles, like the electron. If an electron wave is split into two parts with each part directed around the opposite sides of a magnetic field and then brought back together, there would be a phase lag in one side of that wave, showing it sensed the magnetic field even though it traveled around it. Undaunted by the existing dogma dictating a null effect for the neutrally charged neutron, Cliff and his colleagues performed the test by first designing an ingenious way to separate the neutron wave and have it travel through a magnetic field unencumbered by the return path of that field. Using a ring of a soft ferromagnet, like iron, Cliff constrained the field to stay within that ring while he directed his split neutron waves from his two-crystal interferometer through the center and outside of the ring, alternating every so often which neutron beam went through the center of the ring for good statistics. As no Aharonov-Bohm effect was found, again the neutron was found to stand up to the test (1981).

Another such experiment was Cliff's search for a magnetic monopole on the neutron.[44] Of course, such things were not thought to exist in nature, but if they did, reasoned Cliff, the neutron would be the perfect example. A good test of this phenomenon presented itself when Cliff and his colleagues found that the effective mass of a neutron diffracting inside a crystal is five orders of magnitude smaller than its rest mass.[45] If the neutron possessed a magnetic monopole, it was reasoned, the application of a transverse magnetic field to a highly collimated neutron beam traveling through a crystal would cause large deflections of the beam. After seven weeks of counting neutrons to obtain good statistics in such an experiment, using the same experimental arrangement they constructed for determining the effective mass but with the addition of a transverse magnetic field, Cliff's group failed to detect any beam deflection (1986), thereby reducing the possible magnitude of any such monopole by six orders of magnitude.

In 1994 just prior to receiving the Nobel prize in physics Cliff was awarded the Gregori Aminoff Award, a Nobel-class award for excellence in crystallography, by the Royal Swedish Academy of Sciences. This award was followed in 1995 by the Ilja M. Frank Prize, named in honor of the 1958 physics Nobel laureate. Unfortunately, Cliff lived only six more years to enjoy the accolades for his work. On March 31, 2001, Cliff Shull died.

Throughout his married life Cliff loved to tease his wife, Martha, that he was the "older" (and, therefore, "wiser") of the two of them. Little did he know, however, that she would die four days after him. I think in hindsight that it was fitting that Cliff and Martha died so close together, as their partnership was a real-life example that the combination was better than the sum of the parts. There was also a certain symmetry in the fact that they were born two days apart and died four days apart.

Cliff summed up his professional life in 1994 in a comment to the Nobel videographers: "Nature never runs out of problems. I'm more and more convinced of that. We sometimes lose our patience solving them. And nature is a perfect opponent: it never makes mistakes, and it never lets you make a mistake."[1] Samuel A. Werner described the impact of Cliff's life at his funeral in 2001: "Cliff Shull showed us how to be an experimentalist, a great experimentalist, and how to be a great experimentalist doing it with modesty. It turns out these days I'm still reading Cliff Shull's papers, 40 years later. Some of these very early papers are now coming back to interest. I suspect I'll still be reading some of Cliff Shull's papers 10 years from now."[8] Robert Birgeneau summed up Cliff's life at his 70th birthday celebration in 1985 at MIT: "Through his own excellent example, Cliff taught us the importance of perseverance and integrity of research."[46]

In the preceding I have tried to put into perspective the other coincidences, events, and influences that ultimately directed the path my father, Clifford Shull, followed, culminating in the many discoveries by him and his colleagues related to atomic physics. As one of his three sons, I was in a special position to observe some of these events first hand, although I did not understand the physics or significance of his work until much later when I was a graduate student or practicing materials scientist. Interestingly, although Clifford Shull and Bertram Brockhouse shared the Nobel Prize in 1994 and both corresponded and knew of each other's work, they never worked together.

For more details on C. G. Shull I direct the reader to the original sources referenced herein, most notably the online digitized notes and papers of Cliff cited in note 4. The sources listed in the references helped complete the picture of Cliff as a scientist and mentor. I would also like to thank the many previous students and colleagues of Cliff who provided information to me, most notably Stephen Spooner, Costas Stassis, Herbert Mook, David Moncton, Daniel Greenberger, Michael Horne, Anton Zeilinger, and those I have indicated in the notes and text. I particularly want to thank Cliff's fellow graduate students Bowen Dees and Craig M. Crenshaw for giving me a sense of what it was like to be at New York University in the early 1930s. Lastly, I would like to thank Frank W. Gayle (Chief, Metallurgy Division, National Institute of Standards and Technology) and William D. Phillips (1997 Nobel laureate in Physics) for their terrific job of finding and correcting many of the grammatical errors in this memoir. The letters I have obtained while assembling this memoir and referenced herein will be provided to the Carnegie Mellon University Library so that sometime in the near future they will also become available for view in the online C. G. Shull collection.

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