Terahertz Pioneers

A Series of Interviews With Significant Contributors to Terahertz Science and Technology

AS A TRIBUTE to individuals who have contributed significantly, and over many years, to the terahertz community, and as a guide and inspiration for those who are just beginning their professional association with this field of study, these transactions have included, on a regular basis, a series of biographical interviews with technical researchers who have appreciably impacted the THz community in a positive manner. In order to go beyond a strict technical review and to take better advantage of the information and commentary only available through a direct discussion, these articles take on a less formal style than the research articles that can be found within the remaining pages of the transactions. The Editor-in-Chief has taken some leeway in this regard, for the benefit of communicating more fully the character, experiences, and historic circumstances that have shaped our community and set the directions for our collective research. As a further means of assuring that the true flavor and circumstances of the contributions are expressed in the text, all of the articles are compiled after a face-to-face interview. The final text is shared with, and often helped considerably, by comments from the subject of the article. The Editor-in-Chief, with the support of the IEEE MTT Publications Committee, has chosen to incorporate these biographical articles within the more formal technical journal because of the diversity of disciplines that make up the THz community and the prior absence of a single unifying publication with sufficient outreach to extend across the whole of the RF and optical THz disciplines. The Editor-in-Chief hopes you will enjoy the short diversion of reading these articles as much as he himself enjoys the process of composing them.

This month we bring you a very special *Pioneers'* article that includes not one, but two, long term contributors to THz science, Manfred and Brenda Pruden Winnewisser. This Far-Infrared Spectroscopy team, perhaps better characterized as a family dynasty, also included the renowned younger brother of Manfred, Gisbert Winnewisser (National Research Council of Canada, Max Planck Institute for Radio Astronomy, Bonn, Germany, and University of Cologne, Cologne, Germany), who sadly, passed away in March 2011.

What is remarkable about these individuals is not just their contributions to THz science, but their pure love of research, which has sustained and nurtured them through five decades, and which keeps them buoyant, excited and still working long past the age when most of us would have retired from the stress and competition of a career in science. In addition, the adversities which they had to overcome; Manfred in surviving post-war Germany, forcibly displaced from his family home, at an early age and without a father, and Brenda, who endured in a career that was so severely gender-biased that she effectively was not allowed to compete for a permanent academic appointment in her country of residence. Their stories are a testament to the triumph of will over circumstance and a touchstone that all of us can emulate.

I hope you will enjoy the extra emphasis on personal circumstances and forgive the slightly briefer than usual stress on technical achievement (*most is beyond my limited abilities to understand quantum molecular dynamics anyway*) as you read this account of the careers of one of our very own THz Pioneering families—the Winnewissers.

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I only wish I had reserved more time for this interview with so interesting a pair of science partners, and such a warm and considerate couple as **Manfred and Brenda Winnewisser**. We met on March 6th in Columbus, OH, for a dinner filled with discussions on a wide variety of topics, and then the next morning at their shared office at Ohio State University, where the bulk of the interview was conducted. I sat glued to my chair for more than five hours, listening to their personal stories and learning from their technical insights on a wide variety of topics in far infrared spectroscopy. The tape was still rolling as I was dropped off at the Columbus airport for an all too early flight back to Pasadena. I was very glad to have had the privilege of meeting and getting to know one of the very few life partners in THz science, and certainly the only extended family that might qualify as a *Far Infrared Dynasty*.

Terahertz Pioneers: Manfred Winnewisser and Brenda Pruden Winnewisser

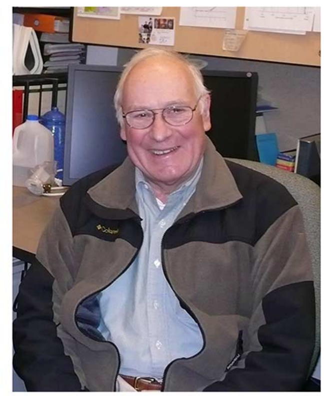
"Equating Hamiltonians to Nature"

Peter H. Siegel, *Fellow, IEEE*

MANFRED WINNEWISSER grew up under extremely difficult circumstances as he struggled through personal loss and the deep deprivations of post-World War II Germany. Manfred's father Georg, a Ph.D. economist who spent time as a post-doctoral fellow at Columbia University, New York, USA, then as an accountant and financial consultant, found a major client in depression-laden pre-war Germany, in a mineral water bottling company. He rented a house as a summer home for his family at a farm in Bad Peterstal-Griesbach, in the Black Forest in 1936, but left as an army draftee in 1939. His family soon moved there permanently from Karlsruhe to escape the bombings. He returned only once, on a brief two-week leave, before being mortally wounded on the Russian front in 1942. On that, his last visit with them in Bad Peterstal, Georg gave young Manfred a briefcase and instructions to take care of its contents, while he swam in the local pool. As one of the last encounters with his father, Manfred remembers with horror, accidently falling backward into the pool, briefcase and all. At age 8, Manfred became the oldest male in this family with three children, trying to learn as much as he could from the old farmer he called "Opa"—grandfather figure—about cows and tree farming, while keeping an eye on his five year old twin brother and sister, Gisbert and Ingrid.

Following the war in 1946, the Winnewissers[1] were forced to abandon their Peterstal refuge in the French Occupational Zone, and were relocated to the American Occupational Zone in the ravaged city of Karlsruhe. Living hand-to-mouth in a half-ruined apartment, the family managed to survive through what was to be an extremely rough next six years. Manfred's ebullient personality and outlook on life seemed to transcend the misery around him however, and at age 13 he was happy to be apprenticed to an electrician in a small firm, with plenty of work to do rebuilding the residential power grid in Karlsruhe. Scavenging through the ruins to collect materials and components, improvising circuits, measuring voltage with two fingers of the right hand, and learning through training classes in practical electronics, Manfred spent two and a half years acquiring the electronics skills that would later become his distinguishing talent amongst his chemistry colleagues.

Brenda Pruden Winnewisser



Manfred Winnewisser

As the Marshall Plan began to replenish and re-establish the German economy, and with significant help from friends and family members, including those in Canada and the US, the Winnewissers slowly recovered some economic stability. Manfred entered a business high school where he also got his first taste of chemistry and physics (*clearly a more classic view of education than we have in many countries today*). Perhaps because his father had an academic degree, or perhaps because of the status such a degree still carried in Germany, Manfred's mother, Irma, supported his desire to enter the Technical University of Karlsruhe in 1953 to pursue a degree in science. Manfred's lack of proficiency in Latin (*they did not teach everything in business school*) forced him to choose Chemistry over Physics, since the director of undergraduate studies, Professor Dvořák, was a bit more lenient about such prerequisites. This was not a serious disappointment to Manfred, as experimenting with volatiles in the kitchen at home was something with which the young Winnewisser had plenty of experience.

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BRENDA PRUDEN spent her childhood in Newark and South Orange, NJ, USA, raised in a conventional conservative American family. Her father was a businessman and her mother was a housewife who had attended Wellesley, a prestigious women's college near Boston, MA, USA. Brenda, who also attended Wellesley, recalls graduating high school the summer before Sputnik made headlines around the world in October 1957. This scientific achievement, accompanied by the first explicit public calls to include women in the pursuit of science, and coupled with the influence of her mother's best college friend, who had taken on a medical career, strengthened Brenda's inclination to pursue a degree in science. However, it was Wellesley Professor Janet Brown Guernsey (MIT trained nuclear physicist and former President of the American Association of Physics Teachers) who served as a role model and mentor for Pruden. After finally discovering *Introductory Physics* in her sophomore year, Pruden declared as a Physics major, and spent the next two years catching up with those who had chosen this path earlier in their school years.

By 1961, when it was time to graduate, Pruden was certain she wanted to pursue an academic career in physics, but competition was stiff, and women were very under-represented in the hard sciences. Guernsey highly recommended, among others, an up-and-coming academic institution in the southern US, and soon after applying, Pruden received a teaching fellowship offer at Duke University. With some trepidation about leaving the northeast, she moved to Durham, North Carolina where she enrolled at Duke, intending to follow in Guernsey's footsteps, and become a nuclear physicist.

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At the Technical University of Karlsruhe, Manfred Winnewisser was pursuing studies in organic chemistry with Rudolf Criegee (known for unraveling the reaction mechanism for ozonolysis [1]—replacement of a carbon-carbon bond with a double bond to oxygen in the formation of organic compounds and the proposer of the Criegee intermediate and the Criegee rearrangement, both considered important reaction processes in atmospheric chemistry). After completing his qualifying exam, Manfred went over to the Institute of Physical Chemistry to try and obtain a position for a Diplom (Masters) project with a dynamic and gallantly reckless young physical chemist, Werner Zeil [2] (who would play a significant role in Winnewisser's career choices). When he entered Zeil's office/laboratory for an interview, Manfred found the chemist sitting up against the wall in a state of *shock*—he had just been attempting to put together a high voltage klystron power supply—unsuccessfully! Zeil blurted out that Winnewisser could have the research position if he fixed the "%$#@&'ing" power supply. Winnewisser's electronics training came to the rescue, and without knowing what a klystron was or did, he soon had the supply in pieces on Zeil's floor, worked out the circuit diagram from a drawing in Walter Gordy's newly published text [3], and brought it to a successful completion, to the everlasting admiration of Werner Zeil.

Zeil aimed to become involved in the new field of microwave spectroscopy, and Winnewisser was charged with helping the group put together a spectrometer. His electronics skills, which he augmented by taking engineering courses in the physics department, were invaluable and much appreciated by his fellow physical chemistry students. When Sputnik was launched, it was Winnewisser who led the team that put up an antenna on the roof of the chemistry building at Karlsruhe (nearly killing himself when he slipped and dived head first off the roof into an open 4th floor window, completely demolishing a chemistry bench in Professor Karl Hasse's lab). He also put together the radio receiver that broadcast Sputnik's 20 and 40 MHz pulses—three days before the electrical engineering department did the same!

Winnewisser measured his first microwave spectra in 1959 (substituted acetylenes) [4] and received his Ph.D. degree in 1960 [5]. He stayed at Karlsruhe one more year after graduating and went on to make measurements on several other molecules with Zeil [6], [7]. His younger brother, Gisbert, followed in Manfred's footsteps (*not for the last time*), and entered the Technical University of Karlsruhe in 1956 where, in 1963, he would receive a Diplom degree in Physics.

Winnewisser's very positive experiences after the war, both with American soldiers and the generosity of his American cousins, combined with his mother's happy memories of five years as a governess in New York City, had instilled a desire in him to travel to the United States. After graduating, he applied for a post-doctoral position with the three best-known microwave spectroscopists of the day. He accepted the first positive response, which was from none other than Walter Gordy at Duke University [8]. In August 1961, he left Gisbert to his studies, and happily made the trip across the ocean to the US, rapidly settling into the already crowded, but very close knit and renowned group in Durham, NC, USA.

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At Duke, Brenda Pruden found the laboratory life style of nuclear physics students to be less than open armed towards the possibility of a first female colleague, and realized that she might have a better graduate school experience, and a wider choice of professional jobs, if she changed direction a bit. The new field of microwave spectroscopy was in full swing, and Walter Gordy had two large groups—one working on gas phase millimeter-wave spectroscopy, and the other using microwave electron spin resonance, ESR, techniques, largely focused on biomolecules. After speaking with Gordy and passing a reference check with flying colors, Gordy told her (in his strong Mississippi accent), "*I haven't had a girl graduate student before, but I'm willing to try*." He informed his group, in her presence, to treat Pruden "*just like one of the boys*." This was fine with Brenda. It was the start of a long and wonderful relationship with Gordy, and his wife Vida, who remain in Brenda's (and Manfred's) memories to this day, as *familial* figures.

Pruden began working with Gordy on radiation damage studies of various forms of amorphous DNA. She found that a hydrogen addition reaction on the thymine base produces a distinct free radical that plays a critical role in genetic damage [9]. She went on to develop the full g-matrix (contains the orientation information for the electron orbits) of the radical in a thymidine crystal [10] and received her Ph.D. degree on these important ESR studies in 1965 [11].

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Manfred Winnewisser truly loved his time in the Gordy lab and reflects on them as the "*Golden* years of his youth". He was a witness to Gordy's election to the National Academy of Sciences in 1963, and the two had a great mutual respect for each other. Thus, when Gordy overheard Manfred talking to a colleague about finding a Ph.D. position for his brother Gisbert, Gordy, quickly sent a telegram to Gisbert offering him a job, later telling Manfred, "*If your brother is half as smart as you are I will take him…*"

Working with Gordy and colleagues Roger Kewley, K. V. L. N. Sastry (who later went to Rice University, Texas to work with Nobel Laureate Robert Curl) and Bob Cook (long time Gordy and De Lucia [12] collaborator; coauthor with Gordy of a definitive monograph on microwave molecular spectroscopy [13]), Winnewisser made great strides in mastering the art of millimeter-wave spectroscopy using point contact harmonic frequency multipliers and detectors, which were notoriously unstable and short lived (see, for example, [12, p. 579]). Soon they were synthesizing and measuring the spectra of small fundamental asymmetric top molecules and short-lived radicals [14], [15], specifically SO and CS, that proved much later to be very abundant in interstellar space.

Manfred remembers one experiment, with honored visitor James Frank (1925 Nobel Prize in Physics) and Gordy looking on, in which he and Sastry were trying to observe the millimeter-wave spectrum of the CS radical in their new nitrogen cooled, glow discharge tube spectrometer. This spectrometer included an overmoded glass tube around 10 cm in diameter between two Teflon lenses where the molecular interactions took place. This arrangement was widely copied and referred to as a *free space gas cell*. Until then, millimeter waves had been squeezed into narrow waveguide cells that limited resolution due to wall collisions. After the discharge of CS_2 had run for a few minutes, Sastry, who was observing the oscilloscope shouted, *"Here are the lines,"* just as the glass chamber exploded! Fortunately no one, especially the distinguished onlookers, was injured.

Winnewisser realized that CS had been condensing on the liquid nitrogen cooling tube. Unfazed, Gordy simply told Winnewisser to have the glass shop make another chamber and to repeat the experiment. This time Winnewisser let the CS and CS_2 flow through the vacuum pump, which of course accumulated the volatiles in the pump oil. He avoided another explosion by then adding O_2 and continuously oxidizing the volatiles, so that the pump exhaust spouted a flame. Several weeks later they had their spectra [16]. *Try getting that experiment through today's safety office!*

During this period, Gisbert arrived at the lab, and the two brothers started looking for the HS radical using an RF discharge absorption spectrometer with H_2S gas. Gisbert in turn was cutting his teeth in the Gordy lab by making point contact detectors. At first the brothers thought they had observed a series of HS absorption lines. Manfred even presented the early data at an American Physical Society conference in Washington, DC [17] to a skeptical audience. As it turned out, the lines were not from HS, but rather fortuitously, from a dynamically more interesting species, H_2S_2 [18]. H_2S_2 (HSSH) would prove to be a model for the extremely rare, but very important class of skew-chain molecules whose form can take on that of an "accidental" symmetric top (a molecule with two moments of inertia that are the same, but not due to symmetry). HSSH has been studied almost continuously for nearly five decades [19] and the subject is still revealing new information about both stratospheric and interstellar chemistry (for example, [20]).

It was now 1965, and in the midst of the work on H_2S_2, Manfred left his instructor position at Duke for a permanent research post back in Karlsruhe under his former mentor and advisor, Werner Zeil. Gisbert remained in the Gordy lab to complete his dissertation. Both brothers continued to work on H_2S_2 through frequent exchanges of data and ideas.

At Duke, the H_2S_2 spectral Q-branch line series at 139.9 and 420 GHz impressed distinguished lab visitor Takeshi Oka (Royal Society Fellow and Davy Prize winner) from the National Research Council (NRC) in Ottawa, Canada, so much that it earned Gisbert an unsolicited fellowship offer at the NRC. This offer arrived about a year afterwards, in March 1967, in the form of an unexpected and terse telegram from Gerhard Herzberg (1971 Nobel Prize in Chemistry), which simply read "FELLOWSHIP APPROVED OFFICIAL LETTER FOLLOWS PLEASE ADVISE WHETHER OR NOT ACCEPTING" [21]. Gisbert went to Ottawa to work with Herzberg in 1968.

Eventually Manfred, Gisbert, and Brenda (*who had taken an interest in both Manfred, and later the infrared spectrum*) together worked out the physical model for this very unusual accidental symmetric top molecule. The work on H_2S_2 and the similar molecules H_2O_2, HOSH, and HNCNH, formed the basis for a career-long set of investigations by the Winnewissers.

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As Brenda Pruden was completing her work with Gordy on the ESR measurements, she began looking around for possible post-doctoral appointments. Manfred, *who was now seeing much more of Brenda*, suggested the lab in Karlsruhe, where Zeil was intending to set up a new ESR facility. Brenda applied for and received a prestigious Humboldt Fellowship from Germany, and in the summer of 1965, she and Manfred left North Carolina for Karlsruhe. They returned to the US briefly in October of the same year to get married in Brenda's home town of South Orange, NJ, USA.

In Karlsruhe, both Brenda and Manfred took up residence in Werner Zeil's group; he as an instructor, and she as a Humboldt Fellow. However the promised ESR system never materialized. The equipment funding, linked to a proposed move to Göttingen University, fell through, and Zeil decided to stay in Karlsruhe. Brenda had no choice but to start working on other research problems, and microwave gas phase spectroscopy was certainly handy. Manfred suggested to her that she work with Gisbert and him looking into the infrared spectrum of H_2S_2, and to join him in a new project, the investigation of the supposedly linear molecule HCNO. *From this point forward, both their personal and professional lives were to be intimately intertwined.*

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Though the laboratory was in Karlsruhe, Zeil's professorship at this time, and Manfred's position, were actually at the University of Kiel, where a new building was under construction. Zeil took up an appointment at Ulm in 1967, and began commuting back and forth from Karlsruhe. Manfred decided this would be a good time to set up a lab of his own. He cashed in on his appointment in the Institute of Physical Chemistry at the University of Kiel and he and Brenda moved from Karlsruhe to Kiel, on the northern coast of Germany.

At this stage, Brenda found she had to make a very hard choice. The Humboldt was expiring, and the physics department at Kiel would not offer Brenda a teaching position, nor was she permitted to apply for a research staff appointment that would allow her to continue to work with Manfred. She was offered an unpaid, informal guest status, under which she would be allowed to pursue her research using institute facilities, but without salary. The only alternative was a long commute to a possible industry job in Hamburg. The lack of a German Diplom precluded high school teaching. Ultimately, she decided to stay at Kiel and work with Manfred.

Soon afterwards however, Brenda did take up an offer from K. Narahari Rao, *who would become a lifelong friend and colleague*, to come to Ohio State University in Columbus for five months in 1968 to work as a research associate in the Department of Physics. It was this visit to OSU that initiated Brenda into high resolution infrared spectroscopy. Both she and Manfred (who came to OSU for the last four weeks of the associate appointment), also encountered, at the Molecular Spectroscopy Symposium in Columbus that year, high resolution Fourier Transform Infra-Red spectroscopy—FTIR. FTIR (the building up a spatial interferogram when a broad band frequency signal being transmitted through a sample, is scanned by translating the reference arm mirror of the interferometer through a path length that determines the spectral resolution; a Fourier transform reveals the spectrum of the transmitted signal) was later to become a major research tool for the Winnewissers. Three papers resulted from this apprenticeship using Rao's large grating spectrometers, not surprisingly about rotationally resolved mid-IR bands of HSSH and HCNO [22]–[24]

Meanwhile Manfred, and Brenda upon her return, continued work on HCNO. This short "six weeks project to get the structure of HCNO", back in Karlsruhe, became the seed of a career-long program, when its rapidly apparent spectral anomalies turned out to be due to quasi-linearity, a concept not yet fully formulated at the time. Other molecules too were measured using the traditional Doppler-limited resolution, free space gas cell, millimeter-wave spectrometer that Manfred had pioneered at Duke. The team managed to reach as high as 800 GHz with hand assembled crystal detectors and multiplier-based sources. In Kiel, Manfred did not have access to the new Bell Labs Schottky diode sources and detectors that were making such measurements much more robust in the U.S. [12]. They managed to do some very impressive work however [25], after Manfred made a considered investment in a PDP8 computer with LAB8 data acquisition hardware. Using the PDP8 they were able to implement spectral averaging for the first time in the millimeter-wave region, achieving not only high sensitivity but also line-center frequency accuracy of under 10 kHz [26].

In 1968, after their experiences at OSU, the Winnewissers realized that high resolution FTIR instruments would rapidly replace existing large optical grating infrared spectrometers. Through the Physical Chemistry Institute at Kiel they acquired a new RIIC FTIR spectrometer (Research and Industrial Instruments Company, Strathclyde, U.K.—taken over by Beckman in the 1970's [27]) with a Golay cell detector. The absorption cell and Fourier transform software were customized in the institute. The hardest problem they faced was performing the Fourier transforms on the very large accumulated datasets generated at the highest resolution of the RIIC. The data from a single spectral scan filled a double-reel punch tape. For HCNO in particular, in order to process the spectrum, the Winnewissers had to make a special trip to the University Computer Center in Hamburg, which they could only use at off-hours (10 PM–6 AM). *These overnight trips to Hamburg were the basis of several colorful stories*.

The advent of the Cooley–Tukey Fast Fourier Transform algorithm, revealed just a few years earlier, helped significantly, and they managed, with difficulty, to make state-of-the-art far infrared FTIR measurements at Kiel. The first rotationally resolved FTIR spectrum of HCNO in the far infrared came out in 1974 [28], clinching the diagnosis of anomalies in the spectrum as a case of quasi-linearity (*more on this later*).

In 1972, Gisbert Winnewisser moved from the NRC in Canada, to an invited position at the Max Planck Institute for Radio Astronomy in Bonn. Interest in interstellar molecules, with their prominent long wavelength spectral features, was growing fast, and far-infrared spectroscopists with a strong experimental background in short lived molecules and radicals were few in number. Coincidentally, Manfred and Brenda moved back south, from Kiel to Justus Liebig University Giessen in 1974, where Manfred took up a post as a full Professor of Physical Chemistry. Brenda, after a similarly fruitless exploration of the employment opportunities for a university physicist in Giessen, continued her work in the lab, as in Kiel, as an unpaid guest scientist.

Bonn and Giessen are only 150 km apart, and Gisbert (who did not yet have laboratory facilities of his own), was able to use the laboratory Manfred had set up thanks to a formal contract between the Max Planck Gesellschaft and the Justus Liebig University in Giessen. He was even able to arrange the contribution of an expensive new microwave spectrometer, relevant for studying interstellar molecules, to Manfred's lab. Thus began a 25 year long series of collaborative spectroscopic investigations at Giessen that would involve Gisbert, Brenda and Manfred Winnewisser, dozens of distinguished colleagues and international visitors, more than 50 post-docs, and that resulted in the graduation of over 50 Diplom and Ph.D. students.

Manfred and Brenda refer to the Giessen years as the second of their Golden Periods. Of the more memorable early results are the excited state HCNO rotational spectra [29], the first studies of accidental resonances in HCNO[30], the successful race to identify the interstellar HNC spectrum [31], [32], the new species C_3OS and its spectrum [33], the interesting paper quantifying quasi-linearity [34] and the HNCS (isothiocyanic acid) isotopomers [35]. All of these results from spectra in the range 100–500 GHz (and those produced in later years at Giessen), helped unravel the complex internal dynamics of small molecules. Many measurements were instrumental in later identifying and understanding the role of light weight molecules in the structure and evolution of the interstellar medium.

In 1982, both Manfred and Brenda took a half-year away from Giessen to visit the NRC in Ottawa and work at the Herzberg lab, now the Herzberg Institute of Astrophysics. At the NRC they used their Bomem (Bomem Inc., Quebec City, QC, Canada; now ABB Analytical Measurements, Zurich, Switzerland), top model Fourier transform instrument, with ~60 MHz spectral line resolution. When they returned to Germany, the Winnewissers were more than ever convinced they had to have an FTIR instrument that could reach into the THz range with "ultra"-high resolution if they were to make significant progress understanding the details of molecular structure and motion. Their commercial FTIR system at Giessen could only attain GHz resolution. At least a ten to one hundred fold improvement was needed for unraveling the subtle quantum behavior of molecules like HCNO, and this is what the Bomem FTIR offered.

Manfred and Brenda worked out all the detailed specifications for an improved FTIR instrument at Giessen. They cataloged all the research that could be accomplished and all the science programs that would benefit. The cost to build the spectrometer would be quite large. The spectroscopy work at Giessen had been well supported over the years by the German scientific research organizations, especially the DFG, Deutsche Forschungsgemeinschaft, but the FTIR project would require an order of magnitude more funds. In order to convince the DFG that this was a worthwhile investment with significant impact and outreach, Manfred brought together a five University consortium that included Giessen, Ulm, Wuppertal, Kiel and Cologne. Not coincidentally, Gisbert Winnewisser had left Max Planck in 1979, and was now a full professor at the University of Cologne, and primarily involved with submillimeter wave astrophysics, one of the major science drivers for the spectrometer.

The DFG expressed some willingness to grant the funds, if the know-how would be German. Bomem was not a German company. The closest competitor in Germany was Bruker Optik GmbH in Ettlingen, but they did not have a product with the required capabilities. Manfred came up with an unusual plan—that the DFG should fund a flexible public/private *collaborative development contract* to build a custom FTIR system with THz capabilities using science know-how from the university consortium in collaboration with engineers at Bruker. Manfred knew that the instrument posed significant technical challenges that could only be overcome by an iterative design-and-build procedure that drew on the scientists (the well-informed users) and the technical engineers (the industrial partners).

Manfred remembers vividly his trip to the DFG referee committee meeting in Bonn where, after they basically accepted the proposal, he made his case for the full funding (more than 1.5 million Marks), and more importantly, he defended the idea of a *development contract*, rather than an out-and-out procurement (something that was almost unheard of at the DFG at this time). He was grilled by the committee on every detail, until in frustration, he threatened to resign from the program if the DFG would not follow through on the flexible design and build contract with Bruker. After making him wait in the lobby for 45 minutes, the committee finally accepted these conditions. One year later, in April 1986, after intensive interactions on the part of both Brenda and Manfred with Bruker, and many discussions with then Giessen Humboldt Fellow, Jim W. Brault (who had built and installed a high resolution FTIR instrument for astrophysics investigations at the Kitt Peak National Observatory in Tucson, AZ, USA), Giessen had a prototype FTIR with a resolution of better than 60 MHz (4 and later 6 meter optical path difference) and the capability of performing a one million data point FFT in less than two minutes [36]. Bruker had originally hoped to build two or three instruments as an advertisement to tout their engineering prowess and help sell their cheaper mainline spectrometer products. Instead the Bruker 120 HR, and now 125 HR, became premier instruments on their own. With continual improvements over the years, Bruker has now sold more than 100 of these unique FTIR systems world-wide, some of which now reach a resolution of better than 20 MHz.

The Bruker 120HR, combined with the science expertise at Giessen and the four other consortium groups, gave German spectroscopy an enormous boost. Over the next 15 years many significant results came out of the DFG investment including work on important chemical reactions in the Earth's stratosphere [36], [37] and NCCN on Titan [38]. A select few of the more than 280 journal papers from the Giessen group between 1986 and 2001 are listed in [39]–[53].

While Manfred and Brenda were establishing the spectroscopy laboratory at Giessen, Gisbert was working on a millimeter/submillimeter radio telescope facility at Cologne. He had visited pioneering millimeter wave astronomer Patrick Thaddeus at NASA Goddard Institute for Space Studies in NYC (currently at Harvard Smithsonian Astrophysical Observatory, Cambridge, MA, USA) and saw his, Thaddeus's, 1.2 meter state-of-the-art radio telescope operating on the top of the Physics building at nearby Columbia University, in the heart of the city (water vapor levels during the winter in NYC were low enough that radio observations up to 200 GHz could be made even in this densely populated urban area). Gisbert took this idea back to Cologne and managed to fund a 3 meter submillimeter-wave telescope through German backing, which he constructed and tested in 1985–86 on the roof of the Cologne University Physics building! This very successful submillimeter wave telescope was then moved to its permanent location in a tower of a castle-like ski-hotel on the top of the Gornergrat (3135 meters) in Zermatt, Switzerland.

The Gornergrat Telescope, operated under the KOSMA laboratory (Kölner Observatorium für Submillimeter Astronomie), was equipped with state-of-the-art room temperature and superconducting tunnel junction heterodyne receivers, and functioned as a world class radio facility for 25 years (until June 2010). It was a highlight of Gisbert's long career in THz science. The observatory was very recently decommissioned and sent to a new working home in Yangbajing, near Lhasa, Tibet. The KOSMA telescope actively supported a large and extremely successful THz receiver development group at Cologne, that fielded a suite of instrumentation up to 880 GHz at Gornergrat and for telescopes as far away as Antarctica, and also provided the motivation for a large amount of supporting spectroscopy work at Giessen.

In 1999, Manfred turned 65 and faced mandatory retirement from his post at Giessen. This was an opportunity that K. Narahari Rao at OSU had been waiting for since 1968, but he was already retired. Frank De Lucia [12] however had not, and he asked (*several times*) if Manfred and Brenda would consider relocating in Columbus, which the Winnewissers remember he referred to as a "big, small town." With few misgivings, the Winneswissers left their home in the *small town* of Heuchelheim, and relocated to the *big small town* of Columbus in 2000. There they set up residence as Adjunct Professors in the Physics department of the Ohio State University.

For the past 13 years, which they refer to as their third *Golden* Period, Manfred and Brenda have been focusing mostly on a more fundamental understanding of the dynamics of near-linear or *quasi-linear* molecules. Unburdened by the demands of running a large research group, or steering the fate of the Physical Chemistry Institute as director, and untethered from the bonds associated with today's very directed grant-based research, they have uncovered, in the quantum energy-momentum manifolds of their quasi-linear molecules, a real-world manifestation of what was thought to be only a mathematical concept—quantum *monodromy*. Monodromy describes mathematically how objects behave as they travel around a singularity. The near-linear structure of such molecules as HCNO, NCNCS, BrCNO, ClCNO, NCCNO and several others studied in detail by the Winnewissers, have a champagne-bottle potential (a rising hillock in the middle of a potential well—like the recessed center of a champagne bottle). As the bending-rotational energy states rise to approach the peak (*monodromy point*) and then traverse it, they produce a discontinuity that can be visualized in the energy-momentum diagram [54]. The Winnewissers explored this behavior in NCNCS starting in 2004 [55]–[57], using the high resolution broad-band millimeter and submillimeter wave FASSST spectrometer at OSU [58]. Instead of 30 lines a day, as in 1985 in Giessen, they could harvest 100,000 lines with the OSU FASSST system in 2004.

The resulting spectra of these quasi-linear molecules reveal the dramatic effects of monodromy on the pure rotational (end-over-end) quantum states of such constructs, which actually include H_2O. Manfred is now pursuing the high resolution bending-rotation THz spectrum of NCNCS at the Canadian Light Source, Saskatoon, Saskatchewan, Canada (CLS is a high energy synchrotron with a very high brightness temperature THz beam line). At CLS, he synthesizes (using his skills as an organic chemist) and then measures, NCNCS using the new Bruker HR125 at the CLS facility. This synthesis led directly to another THz study, namely of the rigidly bent isomer of NCNCS, $S(CN)_2$ [59], [60]. Brenda has now left that undertaking to him, while she pursues several projects in the history of science [61], [62].

Gisbert Winnewisser passed away in 2011 after a long bout with Parkinson's disease. He was one of the individuals I had hoped to interview for this series of articles on Pioneers of Terahertz. Gisbert, Manfred, and Brenda Winnewisser are a true THz family dynasty. They not only helped lay the technical foundations for much of current far IR spectroscopy, but also contributed techniques, data analysis strategies, instrumentation, and unique molecular spectroscopy results that spread from post-war Western Europe to Eastern Europe, Asia and the United States. Remarkable in their dedication and their energy, Brenda and Manfred continue to pursue their love of physical chemistry and chemical physics, and their passion for constructing *Hamiltonians that characterize the natural world*. In a very prescient moment, when I asked about the potential applications of quantum monodromy, Manfred brought out a beautiful photo of a sunflower, whose seed distribution follows the mathematical form of a torus over a circle—a Sol Manifold—and a manifestation of *quantum monodromy*.

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Manfred Winnewisser received the Diplom (Masters) in chemistry in 1956 and a doctorate degree in 1960 from Technical University of Karlsruhe, Germany. He left Karlsruhe in 1961 to take up a post-doctoral appointment and later an instructor position at the Walter Gordy microwave spectroscopy laboratory at Duke University in Durham, NC, USA. While at Duke he met and later married Brenda Pruden, a graduate student in Gordy's ESR group. He returned to Karlsruhe, with Brenda, in 1965 to work with his former thesis advisor Werner Zeil, but soon started his own group at Kiel University in 1967. He was elevated to full Professor in Physical Chemistry in a new post at Justus Liebig University, Giessen which he assumed in 1973. Manfred remained at Giessen for more than 25 years, officially retiring in 1999. He then moved to Columbus, Ohio and took up a post as Adjunct Professor of Physics at Ohio State University, where he resides today. Professor Winnewisser is best known for his extensive technical development in millimeter wave and submillimeter wave spectroscopy as well as far infrared FTIR spectroscopy and applications to the structure and understanding of the rotational and vibrational motions of small molecules with unusual internal dynamics. Most recently, this has led to the demonstration of quantum monodromy in NCNCS, the fundamental property of quasi-linear molecules. During his career, Professor Winnewisser had significant guest appointments at Mississippi State University, University of Copenhagen and National Research Council of Canada. He held a British Council Lectureship fellowship in 1976 and shared the Max Planck Research award with Frank De Lucia in 1992. Dr. Winnewisser is a member of the American Physical Society, the American Chemical Society, Deutche Bunsengesellschaft and Gesellschaft deutscher Chemiker. He is a member and past President (1995–2000) of Justus-Liebig-Gesellschaft zu Giessen, which included running the Liebig Museum. He was on the Advisory Committee (1970–1991) and the Chair in 1989 of the (Western European) Colloquium on High Resolution Molecular Spectroscopy. He also served on the steering committee of the International Conference on High Resolution Molecular Spectroscopy from 1990–1996 and worked continuously to facilitate communication between Western and Eastern European science and technology. Professor Winnewisser has published more than 240 peer reviewed journal papers and contributed to 4 books. He has given more than 60 special invited talks, and continues to work, publish and lecture on his laboratory work.

Brenda Pruden Winnewisser received the B.A. degree in physics from Wellesley College, MA, USA, and a Ph.D. degree from Duke University, Durham, NC, USA, in 1965, where she worked on Electron Spin Resonance in the Walter Gordy microwave spectroscopy laboratory. She received an Alexander von Humboldt Fellowship in 1965, which she used at the Technical University of Karlsruhe and the University of Kiel to learn rotational and vibrational gas phase spectroscopy of several molecules through their microwave and infrared spectra. She held a research position in Physics at Ohio State University in 1968. She taught as visiting professor at Mississippi State University in 1970–1971. She also worked as a guest scientist at University of Kiel, Germany from 1967–1974, University of Copenhagen in 1975, National Research Council of Canada in 1982 and Justus-Liebig University, Giessen from 1974–2000. Brenda was a DFG research associate in the Physical Chemistry Institute at the Justus Liebig University, Giessen, Germany from 1987 to 1991. Since 2000, Dr. Winnewisser has been an Adjunct Professor in Physics at Ohio State University. Dr. Winnewisser has worked on data analysis and infrared spectral analysis techniques of rotationally resolved molecular spectra in the millimeter- to near-infrared-regions, and on molecular dynamics for more than 45 years. She did fundamental work on radiation damage in DNA using ESR techniques while at Duke. At Karlsruhe and Kiel, she contributed to all of the experimental work in the Winnewisser labs. She worked on strategies for analysis of the research on small quasi-linear molecules such as HCNO and NCNCS. While at Giessen, Dr. Winnewisser developed measurement techniques and collected far IR spectra on a variety of important molecules, including intensity determinations for NCCN, relevant for the atmosphere of Titan. Dr. Winnewisser also made the unique mid- and near-IR spectral measurements of solid hydrogen. Recently, Dr. Winnewisser has been working on quantum monodromy, a recently discovered topological property of the bending potential function of quasi-linear molecules. Dr. Winnewisser married and worked closely with her husband, Manfred Winnewisser, as well as maintaining a strong interest in the history of science. In this regard, she has catalogued one complete archive, contributed two American Institute of Physics archived oral interviews, one with Gerhard Herzberg in 1989, and the other with Giessen physicist Wilhelm Hanle, and she is completing a book on physicist Hedwig Kohn which will appear in 2014. Dr. Winnewisser has also translated most of a multi-author textbook on biophysics, edited a book on Fourier Transform Spectroscopy and also edited a biography of German and American physicist Hertha Sponer. Dr. Winnewisser served on the Advisory Board (1992–4) for the Symposium on Molecular Spectroscopy at the Ohio State University and on the Rao Prize Committee since 2002, which she chaired from 2003–2009. She has published more than 130 articles in peer reviewed journals, contributed to 4 books and has given many invited talks. Dr. Winnewisser is currently working on lectures and publications in the history of physics, and doing consulting for her husband in the Physics Department at Ohio State University, Columbus, OH, USA.