THE KAVLI PRIZE

autobiography

Harald Rose at age 5 (to the right) with his mother Anna-Luise and his two year older brother

I was born on 14 February 1935 in Bremen as the second child of my parents Anna-Luise and Hermann Rose who were both mathematically talented. My father grew up in a house where everybody of his family was playing an instrument, my father the piano. He started to study mathematics but was forced to go into business after his father lost his fortune due to the hyperinflation in the early 1920s. My father was very successful in business and became in 1937 the sales representative of the well-known company Kaffee-Hag for the state of Hessen.

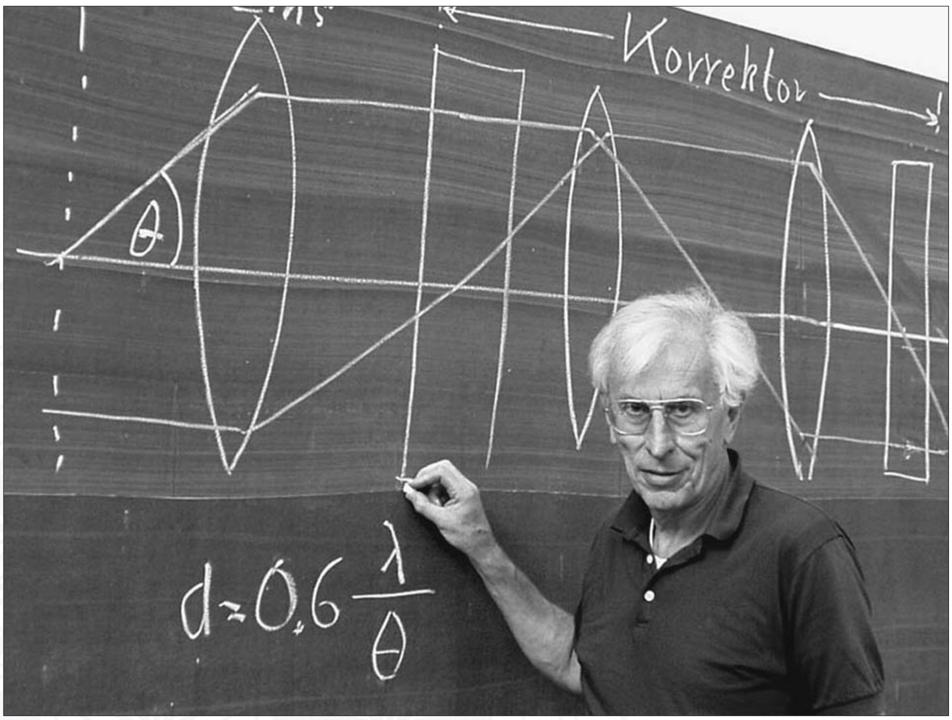
by Harald Rose

We moved to Darmstadt at this year where my father built a very nice house in an exclusive neighborhood called the Mathildenhöhe, which is the focal point of the German Jugendstiel (Art Nouveau). We moved in the house in 1939. One year later my father was drafted to the German Army after Hitler had started World War II. I saw my father only a few times up to 1944. Shortly after his last visit in February 1944 on the occasion of my 9th birthday he was reported missing in action on the eastern front. We never saw him again. On September 11, 1944, our house was destroyed by an Royal Air Force air raid on the city with a loss of the lives of 12000 civilians. Fortunately, my mother and my brother survived and moved to a small village on the country side where I had been evacuated with my school class half a year earlier. Here the war was over for us when the American soldiers arrived in March 1945.

At the end of this year I passed the examination for admission at the Realgymnasium in Darmstadt where my mother had found a job at the tax revenue office. Because normal housing was not available, we had to live in the damp basement of the ruins of our house. Especially during rainy days, the water was dropping through the ceiling and my mother was moving the beds to a dry spot. Moreover, food was very hard to get and we were quite often very hungry between the end of the war and the German currency reform in May 1948.

Since my mother had to work and taking care to make a living for her two children, she had no time for helping us with the school homework. Fortunately, my mother had not to pay in Hessen tuition fees for the Gymnasium, as it was the case for most other states in Germany. During the time at the Gymnasium I became more and more interested in mathematics. Because we had no money to buy the expensive math books, I went to the Hessische Landesbibliothek in Darmstadt, which was lending scientific books to students for free for a given time. Studying the books helped me to understand easily the mathematics in school. As a result, I did almost never anything for mathematics in school but was always the best in the examinations. At the beginning of 1955, I passed the final examination

(Abitur) with excellent marks in the natural sciences.
Owing to my good grades, I was admitted to study at the Technische Hochschule Darmstadt (today Technical University Darmstadt). At that time there was a strongly restricted admission (numerus clausus) because most of the buildings were not yet restored. At that time the financial situation of my family was still critical because my mother had to take a loan from the bank to rebuild our house. Because studying at a state university was free in Hessen, I could afford to go to the university. I wanted to enroll in the department of mathematics and physics. After my mother asked my grandfather for his opinion, he urged my mother that I should study engineering in order to make a living because “Physik ist eine brotlose Kunst”. Owing to his advice I enrolled in electrical engineering. Because a six-month apprenticeship was required, I was fortunate to be accepted by a local supplier of electricity, where I learned the essentials of electrical craftsmanship. This apprenticeship was helpful for me because I was able to do the basic electrical work at home myself. Although I was able to live in our house, I was forced to earn my own living as a construction worker during the vacations.



Harald Rose explaining the functionality of the hexapole corrector in his seminar room at the Institute of Applied Physics of The Technical University Darmstadt in 1997

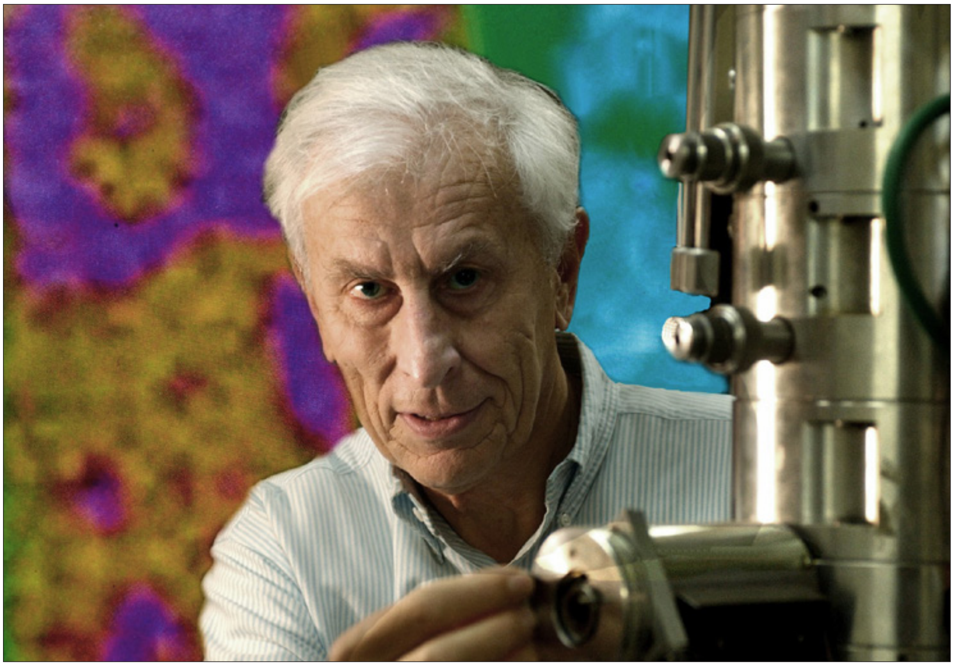
The courses at the university in electrical engineering did not fulfill my expectations because the fundamentals of electricity were hardly discussed. Because I was more interested in the fundamentals of electrodynamics, I decided to follow my own inclinations and changed to physics and mathematics at the end of the semester. My grandfather and my mother were not happy about my decision at that time. The change was not easy for me because I missed the courses of the first semester in physics and mathematics, which always started in April. In order not to lose a year, I acquired the lecture notes of the corresponding courses and studied them during the break before the start of the second semester. This effort helped me to pass in 1957 the examinations for the Vordiplom (roughly equivalent to a bachelor’s degree) after three semesters excluding the semester, which I spent in electrical engineering.

After the Vordiplom I had to decide to graduate either in mathematics or physics because different courses had to be taken for the Diplom examinations (master degree) of each discipline. Because I was not sure which direction to go, I decided to take the courses in both disciplines for some time in order to be sure of my final decision, which I made about one year later due to the fascinating quantum mechanics course given by Otto Scherzer, professor of theoretical physics at the university. Otto Scherzer was a student and assistant of Sommerfeld, who was one of the most famous theoretical physicists in the first half of the 20th century. Like his teacher, Scherzer was outstanding in calculus and had a deep insight into the nature of physical phenomena. In his quantum-mechanics course he showed his excellent pedagogical skills by combining the mathematical formalism with physical explanations of the mysterious nature of the atomic world. Since I managed to solve all exercises correctly, Scherzer offered me a paid position as an assistant for the exercises in theoretical physics. I was very happy for his offer because it gave me enough financial support to make a living on my own without having to work in construction during the brake between the semesters. Moreover, I had free accommodation at my mother’s house, which is in walking distance from the university.

I admired Scherzer for his outstanding abilities as a teacher. Therefore, and because I was already integrated in his institute, I decided to perform my Diplom thesis under his guidance. The topic of my thesis was to find out if it would be possible to detect different atoms in an electron microscope by utilizing their different angular scattering behavior. The result showed that primarily the insufficient technical state of the instruments at that time prevented any realization of this concept. Despite of this frustrating result, my in-depth studies of quantum mechanical scattering prepared the ground for my later work on image formation in the electron microscope. I obtained my Diplom degree at the beginning of 1961. At that time most students and scientists were eager to spend some time at a research institute in the US, which was the center of science. Therefore, I was very glad to obtain an offer from Dr. Fischer, who was on a sabbatical at Scherzer’s institute, to spend a year as a research consultant at the Air Force Cambridge Research Laboratories in Bedford, Mass. My research was focused on the investigation of semi-conductor photodetectors for extremely short light pulses. Although the topic was of practical importance, it did not satisfy my interest.

Returning to Darmstadt in 1962, I was glad that Scherzer offered me to join his institute again for a doctoral thesis. According to Scherzer's suggestion, I agreed to explore in my thesis the imaging properties of non-rotationally symmetric electron-optical systems in detail. The aim was to find feasible systems, which are able to compensate for the spherical aberration in another way as realized in the Scherzer-Seeliger corrector and to find systems corrected for both spherical and chromatic aberration, which are unavoidable for round lenses. This property is known as Scherzer Theorem and prevents atomic resolution in electron microscopes operating at voltages below the threshold of atom displacement. Scherzer derived this result in non-relativistic approximation and it took me some time to show that it stays also valid in the relativistic case. Moreover, I proved that chromatic correction cannot be compensated in any magnetic system with a straight optic axis but that additional electric quadrupoles are indispensable. Although Gottfried Möllenstedt showed in an ingenious experiment that the Scherzer-Seeleger corrector was compensating for spherical aberration, the correction did not improve the resolution of the electron microscope because this was limited by mechanical and electromagnetic instabilities rather than by the optical defects of the lenses. To obtain a real improvement, I calculated the stability criteria, which had to be fulfilled in order that aberration correction is improving the resolution. Nowadays, the effect of the instabilities is known as information limit in contrast-transfer theory. My calculations showed that the number of correction elements must be as small as possible and that they must be mechanically fixed in order to minimize the incoherent aberration resulting from the instabilities. As a result, I designed an electric magnetic multipole corrector consisting of four electric and magnetic octupole elements each of which enabled the excitation of quadrupole and octupole fields and of dipole and sextupole fields compensating for the parasitic alignment aberrations, thus avoiding any mechanical movement.

After I had obtained my doctoral degree, Scherzer offered me a well-paid assistant position to work for my Habilitation, which was required to be granted the "venia legendi", the permission to teach at a university and to become a professor. In my "Habilitationsschrift", entitled "Properties of spherically corrected achromatic lenses", I showed that all correctors known at that time suffered from large off-axial coma unduly reducing the size of the field of view. Therefore, these correctors are not suitable for the conventional transmission electron microscope (TEM). In order to also compensate for the off-axial coma in addition to the spherical and chromatic aberrations and to keep the number of elements as small as possible, I designed a novel five-element aplanatic corrector utilizing symmetry properties. Imposing symmetry properties has proven later as the key for the design of high-performance energy filters, monochromators, the beam separator in the mirror electron microscope, and the hexapole corrector. The corrector was built and tested successfully at Scherzer's institute within the framework of the Darmstadt Project funded from 1972 until 1982 by the German Research Foundation (DFG). The experiments showed that the corrector introduced an unduly large fifth-order aberration. In order to sufficiently reduce this aberration, Max Haider, who joined my group in 1980, replaced the central octopole element of the corrector by a dodecapole element, which he designed and built in the context of his "Diplomarbeit". However, because computer control was not available, he could not align the system within a time, which was shorter than the duration of stability of the optical system. As a result, the resolution of the microscope could not be improved although the project was successful as far as it went up to its end in 1982 after Scherzer passed away.



Testing the mirror corrector of the SMART project in 1998

One year after my Habilitation in 1970, I was appointed as a H2-Professor of Theoretical Physics at the Technical University (TU) Darmstadt. In 1972 Albert Crewe invited me to spend a year in his group at the University of Chicago. During this time I designed an innovative detector enabling efficient phase-contrast in the scanning transmission electron microscope (STEM). Moreover, I calculated the non-localization in images formed by inelastic scattered electrons. The results were confirmed experimentally by Mike Isaacson and John Langmore using the STEM in Crewe's lab. In the following 20 years I pursued the phase problem related with inelastic scattering in particular with Helmut Kohl, who developed an in-depth quantum-mechanical description of image formation in his Ph.D. thesis.

At the beginning of 1976, I left Darmstadt and moved to the US. I was appointed Principal Research Scientist at the New York State Department of Health in Albany, NY, and Adjunct Professor in the Faculty of Physics at RPI, Troy, NY. During my time in Albany I was confronted with the problem of radiation damage, which decisively limits the resolution of electron-microscope images of biological objects.

To minimize this deleterious effect, one of the main tasks of the electron-microscopy group was to find methods, which provided maximum information about the object for the tolerable electron dose. One possibility was the correlation of many low-dose images of identical particles, e.g., ribosomes. Joachim Frank, who joined the group a few months earlier than me, pursued this method over many years. His successful pioneering work was awarded with the Nobel Prize in Chemistry in 2017. My approach was to find means for improving the optical performance of the instrument to such a degree that all scattered electrons could be utilized. In the course of the project, I designed several novel electron-optical elements, such as the magnetic monochromator, the quadrant STEM detector and the aberration-corrected omega imaging filter, which was constructed and successfully tested by Dieter Krahl in Berlin and later incorporated in the Zeiss TEM. Moreover, I proposed the integrated differential phase contrast imaging in STEM, which has been realized in a commercial instrument by FEI several years ago. Together with my coworker Jürgen Fertig we investigated for the first time the propagation of the convergent electron wave in the STEM through thick crystalline objects showing that strong crosstalk between neighboring atomic columns occurs if the cone angle of the incident wave exceeds the Bragg angle.

I returned to Darmstadt University in 1980 where I became a full Professor in the Institute of Applied Physics and perpetuated the research on aberration correction. I maintained links to Albany by yearly visits of several months till 1986. Shortly after returning to Darmstadt, I found in summer 1980 a surprisingly simple corrector for eliminating the spherical aberration of electron lenses employing symmetry conditions, which I had used for the Darmstadt quadrupole octopole corrector. It was known that hexapoles introduce apart from threefold aberrations also a small spherical aberration whose sign is opposite to that of round electron lenses. Hence, if it would be possible to eliminate in some way solely the large parasitic threefold aberrations, the system could serve as a corrector. The calculations showed that this is indeed possible if the system exhibits double symmetry for the paraxial rays, which are not affected by the hexapole fields. The simplest arrangement, which can serve as a corrector for the STEM consisted of two identical round lenses enclosed by two hexapoles. However, funds to realize the corrector were not available because at that time the resolution of all high-resolution electron microscopes were limited by instabilities rather than by the lens defects. At the end of the 1980s the stability of the instruments had advanced to such a state that it no longer was the prime limitation preventing atomic resolution. By adding, in 1989, another round-lens doublet between the objective lens and the hexapole corrector, I found a system resembling an optical aplanat, which is free of spherical aberration and off-axial coma. According to this property, the corrector enables atomic imaging in a stable TEM for a large field of view. Owing to the high symmetry and the simplicity of the electron-optical aplanat, I asked Max Haider for his opinion regarding the successful realization of aberration correction by means of the novel corrector. Max was developing and testing experimentally the properties of a quadrupole-octopole corrector for the low-voltage scanning electron microscope at the European Molecular Biology Laboratory in Heidelberg and, therefore, had to my opinion the best judgement regarding the feasibility of my proposal. To my surprise, Max was convinced from the very beginning that the corrector would work providing genuine atomic resolution. However, in order to realize the corrector, sufficient funding was necessary. Fortunately, we had a very fruitful discussion with Knut Urban about the prospects of successful aberration correction for materials science during the Dreiländertagung at Salzburg in September 1989. Knut Urban, being aware of the importance of aberration correction, suggested to submit a mutual (Rose, Haider, Urban) proposal to the Volkswagen Foundation because all other funding agencies turned down the proposal primarily on the reason that the US had suspended funding for realizing aberration correction. Contrary to the frustrating decision of the other agencies, the Volkswagen Foundation took the risk and started funding in 1991. This support resulted in one of the most successful projects ever funded by the Volkswagen Foundation after Max Haider succeeded in June 1997 to reduce the point resolution of the basic (uncorrected) instrument from 0.24 nm to 0.14 nm giving genuine atomic resolution, as shown by the pictures taken by Bernd Kabius from Juelich.

In 1997, the Berlin electron synchrotron BESSY II was launched and funds were made available for novel projects exploiting the capabilities of the novel photon source. I was asked by Alex Bradshaw and Eberhard Umbach, the organizers of the ambitious SMART project, to become a member of a group of scientists who were engaged in developing an aberration-corrected electron microscope, which could operate as a low-energy electron microscope (LEEM) using reflected electrons and as a photo-emission electron microscope (PEEM) forming images with electrons emitted from the surface layer by photons. The task of my group was the design, the construction, and the testing of the electric-magnetic objective immersion lens, the aberration-free beam splitter separating the incident and the reflected electron beam, and the mirror corrector compensating for the spherical and the chromatic aberration of the lenses. The successful realization of these ambitious tasks after four years was primarily achieved by my excellent and ambitious students Dirk Preikszas, Peter Hartel, and Heiko Müller. Apart from the SMART project, my group was also involved in the Sub-eV Sub-Angstroem Microscope (SESAM) project, initiated by Manfred Rühle, in developing an electron-filtering electron microscope (EFTEM) with high spatial and high energy resolution. In the context of his doctoral thesis, Stefan Uhlemann designed the high-performance MANDOLINE filter, which was built by Zeiss and incorporated in the SESAM microscope. Up to this day the microscope is operating with outstanding results at the Max Planck Institute in Stuttgart.

Despite the great successes and achievements of my group, its high international reputation, and memorandums from numerous scientists and industry, the Technical University Darmstadt abandoned my field of research by effacing my position after my retirement in April 2000. Owing to my excellent contacts with many colleagues in the US, I followed an invitation to spend a year as a Research Fellow at Oak Ridge National Laboratory. Here, I met Murray

Discussion with professor Hannes Lichte at the M&M Conference in 2009

Gibson from Argonne, who aimed for a high-resolution electron microscope enabling any kind of in-situ experiments. Because this condition can only be met with a large object chamber, the objective lens must be corrected for spherical and chromatic aberration for achieving high resolution of about 0.2nm at medium voltages, which are necessary for reducing radiation damage. I accepted the offer of Murray to design the corrected objective lens and moved to Argonne in September 2001. However, I had to stop my work at Argonne at the end of April 2002 when a biopsy indicated that I had prostate cancer in an early stage. Fortunately, the cancer had not spread so that the chances of survival were very good. After surgery at the University of Mainz, it took me more than a year to recover. In the meantime, upon Murray's change as director to the Advanced Photon Source, Uli Dahmen at Lawrence Berkeley National Laboratory (LBNL) became director of the TEAM project. The aim of the project was changed by DOE by requesting a chromatic and spherically corrected medium-voltage electron microscope providing a resolution of 0.05nm. In September 2003, I moved to Berkeley to become a research fellow at the Advanced Light Source (ALS) of LBNL. Because the ASL is located within walking distance away from the National Center of Electron Microscopy (NCEM), I accepted the invitation of Uli to become an advisor for the TEAM project, which started in 2004 and ended successfully in 2009 with a record resolution of 0.047nm, which is about the radius of the hydrogen atom. I designed the TEAM corrector in cooperation with the company CEOS. By replacing each hexapole of the hexapole corrector by an electric magnetic quadrupole-octopole quintuplet, the resulting corrector compensated for the chromatic, spherical aberration, and the coma by preserving the double symmetry.

In 2007, Professor Ute Kaiser at Ulm University invited me to give a lecture on aberration correction, in particular on the design and the functionality of the hexapole corrector. This corrector was part of her new TITAN electron microscope, which was the first commercial aberration-corrected TEM delivered by the company FEI in 2005. Ute Kaiser was interested in visualizing the atomic structure of two-dimensional (2D) objects such as graphene. However, when operating the microscope at the recommended voltage of 300kV the object was immediately destroyed. Fortunately, thanks to aberration correction, the microscope was also able to provide atomic resolution at 80kV, the lowest adjustable voltage of the instrument. Because this voltage is below the threshold voltage for atom displacement in graphene, she was able to image its atomic structure. This result proved that radiation damage is also limiting the resolution of many objects in materials science. Since the knock-on threshold for many radiation-sensitive 2D objects is in the range between 20kV and 80kV, the need for an aberration-corrected low-voltage electron microscope became obvious. Because at these low voltages chromatic aberration exceeds the spherical aberration of the objective lens and large usable aperture angles are necessary for obtaining atomic resolution, the development of a novel corrector was necessary. The high-performance SALVE corrector was obtained by splitting up the central multipole of the Darmstadt quadrupole-octopole corrector in two spatially separated elements. Using this system as a start, the members of CEOS developed the corrector within the frame of the Sub-Angstroem Low-Voltage Electron microscope (SALVE) project initiated and headed by Ute Kaiser. The SALVE project started in 2009 and was interrupted in 2011 after Zeiss terminated the production of TEMs. In 2013 FEI together with CEOS continued with the project, which ended in 2017 with an unexpected success showing that the resolution of the microscope was almost 30% better than originally required by the contract. I became a member of the group of Ute Kaiser at the start of the SALVE project and, in 2015, I was appointed Senior Professor of Ulm University.

Apart from designing electron-optical components and developing the theory of image formation in the electron microscope on a profound quantum-mechanical basis, I was always interested in understanding the basic nature of the electron. In particular, I tried for more than 20 years to understand the origin of the spin, the charge, and the mass of the electron. For this purpose I employed a novel relativistic quantum-mechanical approach, which is closely related with relativistic electrodynamics and with the Dirac theory. Probably, because I do not belong to the elementary-particle community, my novel theory for explaining the structure of elementary particles was ignored and its publication rejected without reviewing. Nevertheless, I could present on December 10, 2019, my novel theory at a special physics colloquium of the University of Ulm and hope that my talk will initiate fruitful discussions on the topic.

Together with a representative of Zeiss at the 2015 Synposium at Ulm University on the occasion of his 80th birthday, showing one half of the omega filter

A get together with his tennis partners in 2012

Harald and Dorothee on a restaurant celebrating his birthday February 14th, 2012

During all the time after I started with school, I was active in sport playing hockey, skiing in winter, and hiking in the Alps in autumn. Hockey is a very demanding sport but the risk of severe injuries increases with age. Therefore, I had to leave it at age 50 and to look for some other activity. It was quite natural that I chose to learn to play tennis because my wife Dorothee was a very talented tennis player, who played in a team at a local sport club. She was willing to give me tennis lessons because there was nobody else who wanted to play with a beginner. Owing to her help I advanced to a state which enabled me to find partners and to play in a team. Although, I cannot play singles anymore owing to my high age, I still play tennis every week with several double partners. Moreover, Dorothee and I go hiking with former hockey teammates and their wives for several days every year. During my scientific life I have had personal contacts with many colleagues around the world. Many of these contacts have become friendships over the years. I appreciate these friendships very much because I consider them as precious gifts. Finally, I want to thank my wife for her support and her patience when I was working on many weekends for many years.