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Honors. Biermann was the recipient of the Copernicus Prize in 1943, member of the Bavarian Academy of Sciences and Humanities and of the International Academy of Astronautics, corresponding member of the Société Royale des Sciences de Liège, member of the Akademie der Naturforscher Leopoldina in Halle (East Germany), foreign associate of the National Academy of Sciences (United States), recipient of the C. W. Bruce Gold Medal of the Astronomical Society of the Pacific (United States) in 1967, associate of the Royal Astronomical Society (England) in 1964, and recipient of the Gold Medal of the same society in 1974. He was a member of the Astronomische Gesellschaft (Germany) and a German delegate to EURATOM.

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BIJVOET, JOHANNES MARTIN (*b.* Amsterdam, Netherlands, 23 January 1892; *d.* Winterwijk, Netherlands, 4 March 1980), *x-ray crystallography, physical chemistry*.

Bijvoet was an x-ray crystallographer who developed a new technique, based on the so-called anomalous scattering of x-rays, that permitted a direct determination of the configuration of molecules and crystals with x-rays alone. In 1950 he was the first scientist to determine the absolute spatial configuration of an optically active organic molecule (sodium rubidium tartrate). Through this crucial experiment, Bijvoet was able to prove that the geometries of the L- and D- structures of an organic molecule with a center of asymmetry, which had been

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proposed arbitrarily by Emil Fischer around 1900, corresponded to reality. Later Bijvoet developed his method into a more general technique to determine the spatial configuration of optical antipodes. Bijvoet was reader of crystallography and thermodynamics at the University of Amsterdam from 1929 to 1939, and professor of general and inorganic chemistry at Utrecht University from 1939 to 1962. In 1951 he succeeded Sir W. Lawrence Bragg as president of the International Union of Crystallography.

Childhood and Education. Jo Bijvoet was born in Amsterdam on 23 January 1892, the third son of Willem Frederik Bijvoet, a paint manufacturer and trader of tar products, and Barendina Margaretha Bijvoet (née Rüfer). His father was a partner in the firm of A. Pleging and Company, but only the fourth son, Frederik, decided to enter the business. All the other sons studied at university, and there was undoubtedly an intellectual and artistic atmosphere in the family; Jo studied music from an early age, and loved to listen to Mozart and other classical composers all his life. His eldest brother, Willem Frederik, Jr., was a gynecologist; his second brother, Bernard, became a well-known modern architect, who also designed the cover of Bijvoet's textbook on crystallography. From 1902 to 1908 his father was a member of the municipal council of Amsterdam.

In 1903 Bijvoet entered the Hogere Burgerschool (a modern secondary school) at the Keizersgracht in Amsterdam, where he had an inspiring teacher of chemistry, H. Hemmes. In 1908 Bijvoet decided to study chemistry at university. In those years a knowledge of classical languages was required for Dutch university degrees, and therefore from 1908 to 1910 he studied Latin and Greek and spent many hours on his passion for music. Bijvoet studied chemistry at the University of Amsterdam from 1910 to 1914, and from 1918 to 1919. He was slightly disappointed by his chemistry courses, but he became enthusiastic about the field of physics. In the second year of his studies he wrote a publication, together with Remmelt Sissingh, professor of experimental physics, about an optical experiment he had done during the physics course. In 1914 he did his *kandidaats* examination (bachelor's degree) cum laude.

In August 1914 World War I broke out, and Bijvoet was called to military service. Although the Netherlands remained neutral during the war, Bijvoet had to stay in the army from 1914 to 1918. He was stationed at Fortress Abcoude, about 9 miles (15 km) south of Amsterdam, and he spent most of his time studying the theories of Josiah Willard Gibbs as well as other works on his favorite topics, thermodynamics and statistic mechanics. After the end of the war, in 1918, he studied physical chemistry at the laboratory of professor Andreas Smits, followed the

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lectures on statistical mechanics given by J. D. van der Waals, Jr., the son of the Nobel laureate, and did his *doktoraal* examination (master's degree), again cum laude, in 1919.

X-Ray Crystallography. After his graduation, Bijvoet became an assistant to Andreas Smits in the department of general and inorganic chemistry in Amsterdam. In those years the recent X-ray studies of William and W. Lawrence Bragg were hotly debated at the Amsterdam laboratory. The Braggs had concluded that crystals of sodium chloride (NaCl), and similar salts, were regular lattices of sodium and chloride ions. Bijvoet agreed, but his supervisor Smits strongly opposed that view; according to Smits, well-defined molecules, such as NaCl, were the cornerstone of inorganic chemistry. Smits decided to begin x-ray experiments at Amsterdam, and asked his students Bijvoet and Albert Karssen to introduce that new technique to his laboratory.

After the discovery of x-ray diffraction by Walter Friedrich, Paul Knipping, and Max von Laue in 1912, and the first determination of crystal structures by William and W. Lawrence Bragg in 1913, several Dutch scientists had quickly entered the new field. Peter Debye at Utrecht and Hendrik A. Lorentz at Leiden made important contributions to the theory of x-ray diffraction. At the University of Groningen, Frans M. Jaeger, professor of inorganic and physical chemistry, started experimental work in 1913, which was the beginning of the Groningen chemical-mineralogical crystallographic school. Later, also in the physics department at Groningen, important research was conducted by Dirk Coster, Frits Zernike, and their colleagues. In 1917 Willem H. Keesom, who had studied with Heike Kamerlingh Onnes and Hendrik A. Lorentz at Leiden, became professor of physics and physical chemistry at the Veterinary School at Utrecht. This was the same school where Jacobus Hendricus (Henry) van 't Hoff had worked in the 1870s, when he developed his important ideas on the carbon tetrahedron. In 1918 the Veterinary School became part of Utrecht University. Immediately after his appointment, Keesom, together with the physicist Nicolaas H. Kolkmeijer, began experimental x-ray analysis of crystals, in close collaboration with Ernst Cohen, professor of inorganic and physical chemistry at the university.

In 1919 the University of Amsterdam lagged behind, and Bijvoet and Karssen decided to go to Keesom's laboratory at Utrecht in order to master the new technique. Their three months of work with Keesom and, especially, Kolkmeijer, initiated a long period of intense collaboration between the crystallographic groups of Utrecht and Amsterdam. After their return to Amsterdam in 1920, Bijvoet and Karssen received grants for the acquisition of

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x-ray equipment and started working on their dissertations. In 1923 Bijvoet obtained his PhD with his dissertation, which was published as *X-Ray Investigation of the Crystal Structure of Lithium and Lithiumhydride*. The fact that it was in English was quite unusual at that time.

The same year, Bijvoet became Andreas Smits's "first assistant," a post that he held until 1929. From 1924 to 1929 he also taught chemistry at the municipal gymnasium (grammar school) of Hilversum, and from 1925 he also taught "special topics from physical chemistry" at the University of Amsterdam as a personal lecturer (*Privat-Dozent*). Meanwhile, he continued his research on x-ray crystallography of simple salts, which resulted in several joint publications with Kolkmeijer and Karssen. In 1926 Bijvoet and Karssen worked for a few months in the laboratory of Sir W. Lawrence Bragg at Manchester, which was one of the international centers of chemical crystallography research. In 1928 Kolkmeijer, Bijvoet, and Karssen published the first Dutch textbook on x-ray crystallography, *Röntgen-analyse van kristallen*. The book went through revised editions in 1938 and 1948, was translated into German in 1940, and was published in English in 1951. As with all Bijvoet's textbooks, it was extremely well-structured and clear, and was considered by Paul Ewald, the doyen of German crystallography, to be the best introduction to the field.

Building on his stimulating international experience at Manchester, Bijvoet soon became one of the leading x-ray crystallographers of the Netherlands. In addition to his diligence, he was open to new developments, and he one of the first Dutch chemists—as contrasted to physicists—who thoroughly studied quantum mechanics. In 1928 Bijvoet was the first Dutch x-ray crystallographer to apply Fourier analysis to the determination of crystal structures, shortly after it had been introduced to crystal analysis by Bragg, following theoretical studies in 1924 by P. S. Epstein and Paul Ehrenfest (at Leiden University). Together with Anton E. van Arkel at Leiden University and Jan de Boer at the Philips company, Bijvoet belonged to a small group of "modern" physical chemists and crystallographers in the Netherlands who deviated from the classical thermodynamics and phase rule school—of which Andreas Smits and Ernst Cohen were typical examples—that dominated university research.

Reader at the University of Amsterdam. In 1928, after the retirement of Eugène Dubois—the discover of the *Pithecanthropus erectus* (or *Homo erectus*), the "missing link" between man and ape—as professor of geology, mineralogy, crystallography, and paleontology, the municipal council of Amsterdam decided to completely reorganize and expand the geology department of the University. Hendrik A. Brouwer, younger brother of the renowned

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mathematician L. E. J. Brouwer, was appointed professor of general and practical geology, with the task of establishing a large new geological institute. When in 1932 an impressive new laboratory was opened, Brouwer succeeded in attracting two more professors, a reader, and a number of assistants. The reader was Bijvoet, who in February 1929 was given the task of teaching crystallography, general and propaedeutic descriptive mineralogy, thermodynamics, and their applications to chemical problems. It was quite a hybrid position; attached to the geological institute, Bijvoet was supposed to lecture not only to the geology students, but also to students of chemistry and other natural sciences. His economic position secured, Bijvoet in April 1930 married the pharmacist Marie Hardenberg, who had been among his students five years earlier. They had three sons and one daughter.

In his new position, Bijvoet had hoped to expand considerably his research in x-ray crystallography. He met with strong opposition, however, from Brouwer, who doubted the relevance of x-ray work for mineralogy, and who wanted Bijvoet to limit himself to classical, descriptive crystallography and mineralogy. A deep, long-lasting conflict resulted. When the new geology laboratory was opened in 1932, there were no facilities for crystal analysis with x-rays, no budget for Bijvoet, and an injunction by Brouwer that students of chemistry would not be allowed to work at the institute. Therefore, Bijvoet continued to work in the chemical laboratory of Andreas Smits, almost without any funding. In the course of the 1930s the professors of physics informally gave part of their budget to Bijvoet, convinced as they were of the importance of his research. They also decided that all students of physics should follow Bijvoet's lectures on x-ray crystallography.

Despite these difficult circumstances, Bijvoet became a successful and widely admired lecturer. He taught x-ray analysis of crystals to undergraduates, and for advanced students he introduced a new course on "chemical thermodynamics," which was at that time unique in the Netherlands. In addition to these courses for large audiences, he organized informal study groups on Saturday afternoons on Linus Pauling's books *Introduction to Quantum Mechanics* and *The Nature of the Chemical Bond*, on statistical mechanics, and on the so-called "dynamical theories" of x-ray and electron diffraction proposed by Paul Ewald, Max von Laue, and Hans Bethe.

In his research during the early 1930s, Bijvoet continued the x-ray analysis of relatively simple inorganic crystals. He focused on halides and dihalides such as HgBr_2 , PbBr_2 , PbFBr , PbFCl , Ag_2HgI_4 , AlF_3 , and $\text{Hg}(\text{NH}_3)_2\text{Cl}_2$. Along with Bijvoet's technician Bram Kreuger, a small, enthusiastic group of PhD students and assistants did most of the practical research: Herman J. Verweel (PhD

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1931), Willem Nieuwenkamp (1932), Jan Ketelaar (1933), Caroline (Lien) MacGillavry (1937), and Eelko Wiebenga (1940) and Gerard Rieck (1945), who finished their dissertations with Bijvoet after he left Amsterdam. All of them (except Verweel, who died in 1937) became university professors of crystallography, or physical chemistry. In this way, the approach of the successful Amsterdam-Utrecht school spread to almost all other Dutch universities.

The Phase Problem. Apart from tedious calculations, which were typical of x-ray crystallography in those years, Bijvoet and his students were confronted with several scientific problems during their investigations of the (di)halides, which presented great challenges: polymorphism, molecular rotation, irregular occupation of lattice vacancies, and so-called “twin formation” of crystals. Initially, the crystal structures were solved by the trial-and-error method: on the basis of chemical and thermodynamic considerations, a plausible structure was proposed, the x-ray diagram associated with that structure was calculated, and it was then compared to the x-ray reflections that had been measured. Differences between the experimental data and the calculations led to new assumptions about the specific crystal structure, and new calculations were made. This procedure was repeated until an almost perfect agreement between experiment and calculated intensities was reached.

For complicated molecules, this approach was in most cases impossible. The introduction of the mathematical technique of Fourier synthesis in the late 1920s was a great step forward. In principle, if the amplitudes and phases of all the Fourier density waves, belonging to a certain structure, were known, then that crystal structure could be calculated deductively from these data. In practice, however, only the intensities (amplitudes) can be measured by x-ray analysis. This fact definitely put the so-called “phase problem” on the research agenda of crystallographers. Bijvoet started to become fascinated by the phase problem during the 1930s, and it occupied him for the rest of his career. He had been the first in the Netherlands to use the Fourier method, and he also was an early adopter of new methods with which the phase problem could be circumvented, or (partly) solved. In 1934 a great advance was made by the physicist A. Lindo Patterson in the group of quantum physicist John C. Slater at the Massachusetts Institute of Technology (MIT), with the help of the mathematician Norbert Wiener. Patterson developed an adapted Fourier function—the Patterson function—that circumvented the phase problem by proposing a mathematical series of quadratic Fourier density functions, in which only the intensities of the x-ray reflections played a role. Two years later, J. Monteath Robertson, working in the group of Sir William Bragg at the

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Royal Institution in London, developed the so-called isomorphous replacement method that was applicable to structures in which an atom could be replaced by a “heavy atom”—for instance, Cl by Br; or S by Se; or H by Ni, or by Pt—without disturbing the original structure. From a comparison of the X-ray diagrams of crystals with and without the heavy atoms, Robertson and his assistant Ida Woodward in 1936 succeeded in solving the Fourier synthesis of phthalocyanin ($C_{32}H_{18}N_8$), a complex centrosymmetric molecule governed by sixty independent parameters for the carbon and nitrogen atoms. It was the first organic structure deduced directly from x-ray data, without any previously chemical assumptions. According to the crystallographer Dorothy Crowfoot Hodgkin, the Nobel laureate, it was “the first purely physical demonstration of the truth of organic chemistry” (quoted by Krom, 1946, p. 13). Bijvoet was delighted by Robertson’s research and used it as a paradigmatic example of the power of x-ray analysis in his lectures and textbooks.

The new ideas of Patterson and Robertson were soon used by Bijvoet in his own research. In 1936 Bijvoet and his students and colleagues Verweel, MacGillavry, and Rieck determined the structure of succinic acid with the help of Fourier and Patterson synthesis. It was the first organic substance investigated by his group, and the first time that the Patterson method was applied in the Netherlands. From then on, Bijvoet shifted his attention increasingly to the x-ray analysis of organic molecules, and he asked his student Wiebenga to study a number of urea compounds. This research was continued at Utrecht University, where Bijvoet was appointed to a full professorship in 1939. In 1941, after Andreas Smits’s retirement in 1940, Smits and Bijvoet were succeeded by Bijvoet’s students Jan Ketelaar, who took over his lectures on chemical thermodynamics, and Lien MacGillavry, who very successfully continued the x-ray research at Amsterdam.

Professor at Utrecht University. After the retirement of Ernst Cohen in 1939, Bijvoet succeeded him as professor of general and inorganic chemistry at Utrecht. He had a high teaching load, up to ten lectures a week, and he was responsible for all lectures on physical chemistry, with the exception of those on colloid chemistry and electrochemistry, which were taught by his colleague Hugo Kruyt (and later, Theo Overbeek). Bijvoet’s and Kruyt’s research groups each occupied a floor in the so-called Van ’t Hoff Laboratory of Utrecht University. Jacobus Henricus (Henry) van ’t Hoff was one of Bijvoet’s great heroes, and on several occasions he noted the ways in which he was following in Van ’t Hoff’s footsteps: studying with Van ’t Hoff’s successors at Amsterdam, learning the x-ray techniques in the Veterinary School, working in the laboratory named after Van ’t Hoff, and, eventually, determining the

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absolute geometrical configuration of non-symmetrical organic substances with the help of x-rays.

In his inaugural lecture of November 1939, Bijvoet gave a broad overview of his future research and teaching. He paid attention not only to x-ray analysis, but also to quantum theory, statistical mechanics, chemical thermodynamics, and reaction rate theory. And indeed, in the years to come, Bijvoet would modernize the chemistry curriculum at Utrecht completely. He introduced new courses on atomic theory, crystal chemistry, chemical thermodynamics, statistical thermodynamics, theory of the chemical bond, and the Debye-Hückel theory of electrolytic solutions. His lectures were delivered enthusiastically, though the material presented was difficult. As one of the premier science professors in the country, he tried to stimulate dialogue with his lecture audiences, and he organized small-sized classes around the solution of practical problems in x-ray analysis and thermodynamics. Like his textbook on the x-ray analysis of crystals, his textbook on chemical thermodynamics was well received and went through numerous editions.

Bijvoet stayed at Utrecht University until his retirement in 1962. During the years at Utrecht he created a productive crystallographic school and supervised numerous dissertations. In 1952 Bijvoet's group left the Van 't Hoff Laboratory and moved to a converted large villa the Laboratory for Crystal Chemistry, called the "Crystal Palace" by the students. Bijvoet's private home was part of that building. Four years earlier, in 1948, Bijvoet and Wiebenga, who in 1946 had become professor at Groningen University, had founded the organization *Fundamenteel Onderzoek der Materie met Röntgen- en Electronenstralen* (FOMRE; Fundamental Research of Matter with the Help of X-rays and Electron-rays), which, under the auspices of the Dutch national foundation for pure scientific research, donated funding for x-ray equipment and computers to the Dutch crystallographic research groups. Computers were introduced into Dutch crystallographic research only at the end of the 1950s, but by 1956 Adriaan J. van Bommel in Bijvoet's laboratory used an "I.B.M. calculating punch type 604" for the time-consuming Fourier additions. It replaced the use of Beever-Lipson strips for these calculations, which had been introduced in 1936. As in Amsterdam, several of his research students at Utrecht became professors of crystallography, inorganic chemistry, or physical chemistry. In the 1970s almost all chairs of chemical crystallography in the Netherlands, and three chairs at universities in Belgium, were occupied by Bijvoet's students.

Anomalous Scattering and the Absolute Configuration of Molecules. At Utrecht, Bijvoet continued the search for the development and improvement of so-called "direct

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methods" of x-ray analysis, which he had begun at Amsterdam. The ultimate goal was the deduction by means of Fourier synthesis of the structures of molecules and crystals directly from the experimental x-ray data, without the help of chemical considerations or trial-and-error procedures. Robertson had only been able to determine the structure of phthalocyanin because of the fact that the molecule was centrosymmetric, with the heavy atom at its center. In 1940 Bijvoet developed the important insight that by combining the Patterson synthesis with the heavy atom and isomorphic replacement methods of Robertson, it would be possible to also determine the structures of molecules in which the heavy atom was in an arbitrary position. With Patterson's method it would be possible to determine the position of the heavy atom, and by comparing the intensities of isomorphic molecules with and without a heavy atom, the phases could be calculated from intensity differences, and the rest of the molecular structure could be unveiled. Together with his assistant Wiebenga, who had followed him to Utrecht, and his PhD student Cornelis J. Krom, Bijvoet applied this new method successfully for the first time in the structure determination of three isomorphic camphor derivatives: α -Br-, α -Cl- and α -CN-camphor. Although teaching at the Dutch universities almost came to a halt in 1943, university research continued during World War II. In January 1944 Bijvoet and Wiebenga published their new method in a German journal. Full details were presented in Krom's dissertation of 1946.

After this first success, Bijvoet decided to embark on the structure determination of the far more complex molecule strychnine, a molecule without a center of symmetry. This "attack" of non-centrosymmetric molecules with the help of x-ray techniques was partly inspired by Bijvoet's colleague Fritz Kögl, professor of organic chemistry at Utrecht, who held the view that the stereochemistry of, for instance, amino acids played a role in the development of cancer tumors. In a "neck-to-neck race with the organic chemists" Robert Robinson and Robert B. Woodward, Bijvoet and his students Cornelis Bokhoven and Jean C. Schoone in 1947 obtained a first rough Fourier synthesis of the sulphate and the selenate (W. L. Bragg in Ewald, 1962, p. 131). In the following years they succeeded in making a complete determination of the structure of strychnine by constructing a Fourier series that contained a double number of terms, namely those of the strychnine molecule and its mirror image. With the help of geometrical considerations and tedious calculations, Bijvoet and his team arrived at the correct stereochemical structure. Their result was confirmed by the research of Sir Robert Robinson.

Bijvoet and his team were the first to determine a non-centrosymmetrical molecular structure with the help of x-ray diffraction. This was a great success, but the

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methods had been complicated, and Bijvoet was not completely satisfied because non-x-ray, geometrical considerations had played a role. In 1948 he suddenly realized that anomalous scattering of x-rays could possibly provide a method for distinguishing between a non-centrosymmetrical molecule and its mirror image by means of x-ray analysis alone. It was this idea that would bring him world fame among the x-ray crystallographers.

Many crystallographers held the view that Friedel's law, formulated in 1913, made any attempt to distinguish between a molecular structure and its mirror image by x-rays alone an illusion. Georges Friedel's law says that the reflection of the front side of a plane in a crystal lattice is identical to the reflection of its back side. As early as the 1920s Nicolaas Kolkmeijer and Bijvoet were among a small number of crystallographers—including Max von Laue—who doubted the general nature of this law. In 1930 the physicist Dirk Coster at Groningen University showed with the help of anomalous scattering that crystals of zinc blende (ZnS) gave different reflections in one direction, and its opposite. This was an important result, which meant that Friedel's law does not apply in the case of anomalous scattering on non-symmetrical structures (in the case of ZnS there are successive Zn and S planes, so one side of the crystal has a Zn plane facing outward, and the other side an S plane). Anomalous scattering takes place when the energy of x-ray radiation comes close to the energy difference between two electron orbitals in a molecule. In those cases the x-rays are not only reflected by the electrons, but also excite the electrons to a higher orbital, with the end result that a phase shift occurs between the reflection at the front side of a plane, and the reflection from its back side. "Now x-ray analysis not only detects a difference," Bijvoet commented on Coster's research, "but it concludes—and this is, of course, completely impossible to the human eye—that it is the dull plane that has the Zn side facing outward: for the dull plane is found to give the weakest reflection and, as has been argued, the weakest reflection is that of the Zn plane" (Bijvoet, 1955, p. 76).

In 1948 the results of Coster's experiments were largely forgotten, but Bijvoet remembered them, and realized that there was an analogy between the non-symmetrical zinc blende crystals and the non-symmetrical carbon atoms that occur in many natural organic products. The following year he published a short notice stating that anomalous scattering could solve the phase problem in x-ray analysis. The different intensities between a reflection and its opposite—later called "Bijvoet differences"—made it possible to calculate the phase of a reflection. During the next year Bijvoet and his students Antonius (Ton) Peerdeman and Adriaan J. van Bommel tried to find experimental proof for this idea. They chose a substance, the sodium rubidium salt of tartaric acid, whose structure

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was known, apart from its left- or right-handedness. Tartaric acid had played a role in Van 't Hoff's seminal publication of 1874 on stereochemistry, and Emil Fischer had given natural tartaric acid the so-called D-configuration by convention. There was only a 50 percent chance that Fischer's convention corresponded to reality.

In 1950, after complicated experiments that required up to 230 hours of continuous measurements, supervised day and night, because of the great losses of intensity inside the zirconium x-ray tube, Bijvoet and his team finally succeeded in establishing the expected effect. In Bijvoet's own words: "Exciting also was our first record with anomalous scattering, which required a continuously watched exposure of some hundreds of hours. It had to be successful in view of an intended journey, and was daily threatened with failure because of the improvised Zr-tube and the freakishness of a pump that had been hurriedly put back into use. Twenty-four hours before the time of departure half of the Weissenberg (deflection 0/180°) was developed and revealed nothing, the next day the further exposed other half (0/-180°) showed the effect looked for" (Bijvoet, 1962b, p. 530).

Early in 1951 these results were published, and they were recognized as a great step forward. It appeared that the Fischer convention, purely by accident, had been correct. The fact that Bijvoet was the first to prove this result experimentally made his name also well known outside the world of crystallography. Nevertheless, it would take several years before anomalous scattering was generally applied in x-ray analysis. During the 1950s Bijvoet and his team worked hard on an improvement of the new method. In 1955 S. W. Peterson, in Bijvoet's laboratory, succeeded in determining the spatial configuration of the HCl and HBr salts of the amino acid tyrosine, solely by using anomalous scattering and the isomorphic replacement method. This was the first determination of a previously unknown structure by direct Fourier synthesis and anomalous scattering. The following year, Bijvoet and Peerdeman—who in the meantime had found that conventional copper tubes could replace the zirconium tubes in these experiments, a fact that greatly improved the precision of their results—succeeded in determining the structure of a non-centrosymmetrical crystal, without using the replacement method. This was again a great step forward, because in principle any single structure could now be determined with this technique. In 1955 Ray Pepinski and his group in Auburn, Alabama, devised an adapted Patterson function of the anomalous differences, which proved to be an important tool in making the use of anomalous diffraction more popular. In the 1960s the structures of important proteins, such as hemoglobin, were determined with an array of techniques, including anomalous scattering. And in the 1970s and 1980s

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anomalous scattering became part of the standard repertoire of x-ray crystallography (Blow, 2003).

For his work on the structural determination of organic molecules, by anomalous scattering in particular, Bijvoet received many honors and distinctions. He was elected a member of the Royal Netherlands Academy of Sciences in 1946, and a foreign member of the Royal Belgium Academy of Sciences and Arts in 1945, of the Royal Society of London in 1972, and of the Royal Swedish Academy of Sciences. In 1954 he was awarded the Cresner Peny Prize of the Société Chimique Belge. He received honorary doctorates from the Technical University of Delft (1967), the ETH Zürich (1970), and the University of Bristol (1971).

The International Union of Crystallography. In 1946, at a conference in London, Sir W. Lawrence Bragg, Paul Ewald, and some other crystallographers took the initiative to found an international organization on crystallography. Bijvoet became a member of the organizing committee that prepared the establishment of the International Union of Crystallography (IUCr) in 1948. It was also decided that the Union would publish a journal, the *Acta Crystallography*, together with Cambridge University Press. At the first congress of the Union, in 1948 at Harvard, Bragg was elected as its first president. In 1951, at the second congress, in Stockholm, Bijvoet was elected as its second president. During his term, held until 1954, he helped to give the Union a solid financial basis. Starting in 1950, Bijvoet was also a member of the committee that edited the *Structure Reports* on behalf of the IUCr. He personally edited nine volumes of the reference work with great care.

After his retirement in 1962, Bijvoet taught chemical thermodynamics for one year at Eindhoven University of Technology, before he started to live in the countryside, in the eastern part of the Netherlands. Every few weeks he visited his old laboratory at Utrecht, discussed their work, and read the latest literature in the library. The topics he studied he discussed in colloquium with students of nearby Twente University, who visited him at home, together with their professor, Dirk Feil, who had been a student of his.

Together with Willy Burgers and Gunnar Hägg, Bijvoet in 1969 and 1970 edited two volumes for the IUCr with *Early Papers on Diffraction of X-rays by Crystals*. It was an enormous enterprise to select almost 200 papers from the literature up to 1935, and then to select parts of these texts. The two volumes "were the outcome of his original and cherished idea that welding together appropriate parts of these papers into a continuous story made far better reading than a textbook" (Groenewegen and Peerdeman, 1983, p. 37). As was the case with all of

Bijvoet

Bijvoet's books, this work is very well structured and clear. Not surprisingly, it also contained large parts of Friedel's and Coster's original papers.

Bijvoet kept an active interest in x-ray crystallography until an advanced age, despite the deterioration of his physical health. He passed away on 4 March 1980, at the age of eighty-eight.

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Ernst Homburg

BIRKHOFF, GARRETT (b. Princeton, New Jersey, 10 January 1911; d. Water Mill, New York, 22 November 1996), *abstract algebra, computing*.

Birkhoff was the son of mathematician George David Birkhoff and Margaret Grafius Birkhoff. George Birkhoff, the father, was the first American mathematician to gain wide respect in Europe. Garrett Birkhoff is more remembered for promoting new conceptions than specific theorems. His most important single result was a theorem that instituted a conception, the *Birkhoff variety theorem*, originating modern universal algebra. He showed the power of deceptively simple algebraic properties and the feasibility of more complex and realistic applied mathematics, and he was among the first mathematicians to rely heavily on computers.

Lattices and Universal Algebra. Entering Harvard College in 1928, Birkhoff aimed at mathematical physics. Physics led him to partial differential equations, which in turn led to more abstract ideas, including Lebesgue theory and point-set topology. Curiosity led him to finite groups. After graduating in 1932, he went to Cambridge University for physics. That July, though, he visited Munich and met Constantin Carathéodory, who pointed him towards algebra and especially van der Waerden's great new textbook *Moderne Algebra* (Berlin: Springer, 1930). Back in Cambridge he switched to algebra with group theorist Philip Hall.

Birkhoff turned the study of subgroups, subrings, and so on into two branches of mathematics. The intersection $H \cap K$ of subgroups of a single group G is also a subgroup of G . The union $H(K)$ of subgroups of G is generally not a subgroup because an element of H and another of K may