NATIONAL ACADEMY OF SCIENCES

ARTHUR MICHAEL

1853—1942

A Biographical Memoir by
LOUIS F. FIESER

Biographical Memoir

NATIONAL ACADEMY OF SCIENCES
WASHINGTON D.C.

Arthur Michael

ARTHUR MICHAEL

August 2, 1853–February 8, 1942

BY LOUIS F. FIESER

THE FOLLOWING MINUTES were placed upon the records of the Faculty of Arts and Sciences of Harvard University at the meeting of May 18, 1943.*

"Arthur Michael, Professor of Organic Chemistry, *Emeritus,* died on February 8, 1942, in Orlando, Florida, in the eighty-ninth year of his age. Michael was born in Buffalo, New York, on August 7, 1853, the son of John and Clara (Pinner) Michael. He attended the Briggs Classical School in Buffalo. No formal classes in chemistry were held there at that time but Michael had special instruction in this subject at school from one of his teachers, and he performed the experiments by himself with great enthusiasm in a laboratory which his father had fitted up for him at home.

"Thereafter, Michael had planned to go to Harvard College, but a serious illness intervened. As a result the Michael family, in the summer of 1871, went for a long sojourn in Europe. They arrived in Berlin just in time to see the German Army, fresh from the Siege of Paris, march triumphantly down *Unter den Linden.*

"After he had recovered from his illness and after an interval of preoccupation with art and literature, Michael suc-

---

* E. W. Forbes, L. F. Fieser, and A. B. Lamb, "Arthur Michael," *Harvard University Gazette* 38(1943):246.

ceeded, in spite of his meager chemical training, in gaining admission to the Chemical Laboratory of Professor Hofmann at the University of Berlin. A year later, Michael transferred to Heidelberg for two years of study under the renowned Bunsen, who ever remained his scientific paragon. He returned to Berlin in 1876 for two years of study, and it was then that he began the execution and publication of his remarkably long series of brilliant and important researches. Hofmann was the outstanding organic chemist of Germany and his laboratory at that time was the focal point of the world for research in organic chemistry, and there Michael became acquainted with many of the future leaders in that field, among them Ira Remsen and our own Charles Loring Jackson. Michael concluded his student years by spending another year at the *École de Médecine* in Paris under the great Wurtz.

"In 1880, Michael returned to America, and after a short period as Assistant in the Chemical Laboratory at Tufts College, was appointed Professor of Chemistry at that institution. He was able to devote practically all of his time to research and with the aid of private assistants and graduate students prosecuted his investigations with great energy and success. Among the graduate students who came to study with him at that time was Miss Helen Abbott of Philadelphia. She and Michael were married in 1889, and after an 18 months' tour around the world, Michael accepted a position as Head of the Department of Chemistry at the recently established Clark University. This position soon proved most uncongenial, and after a few months he resigned and established a residence and a private laboratory on the Isle of Wight, where he pursued his researches for four years. In 1894, he resumed his professorship at Tufts College and remained there until 1907 when he became Professor *Emeritus,* whereupon he established a private laboratory on his estate at Newton Center.

"In 1912, Michael was appointed Professor of Organic Chemistry at Harvard. He gave no lecture courses. At first his research students and his private assistants worked with him in his laboratory at Newton Center, but during his later years, they carried on their experimental work at the Converse Laboratory, reporting at frequent intervals to Professor Michael at his home. Michael became *Emeritus* here in 1936, nineteen years after he had taken a similar status at Tufts College.

"Next to chemistry, Michael's chief interest was in art, especially ancient and medieval art. He began collecting at an early date and his home in Newton was a repository of thousands of rare objects of art. Through his friendship with Professor Fenollosa, his attention had been directed particularly to oriental art, and objects from the Orient were numerous and conspicuous in his collections. He also had a fine collection of Early American silver. As might have been expected, Michael's erudition regarding the innumerable items of his collection was encyclopedic. At his death he bequeathed his American silver to the Smithsonian Institution and the remainder of his collection to the Albright Art Gallery in his native city of Buffalo.

"As a young man, Michael passed many of his vacations among the mountains; the Alps, the Canadian Rockies, and the Selkirks. Indeed, he became a real mountain climber. Thus, in 1897, he was in the party that made the first ascent of Mount Lefroy, and a few days later, with Professor Fay of Tufts College, he made the first ascent of Mt. Victoria. These are the two splendid ice-capped peaks which dominate the vista at Lake Louise.

"Michael was an eager, alert, but retiring personality, deeply immersed in his scientific and artistic pursuits. He had few intimates and he shunned publicity. Indeed, he declined to accept the award of a famous medal because of the publicity which this would entail. As a teacher, he was stimulating and inspiring and uncompromising in his insistence on thoroughness and accuracy. In his home, among his beautiful Chinese porcelains and bronzes, his Greek and Roman statuettes, his medieval works of art, with his extraordinary cosmopolitan background of experience and acquaintance, he was an incomparable host.

"Michael was always very fond of children, although he never had any of his own. It is not surprising, therefore, that in his will, after disposing of his art collection, his library, and his chemical apparatus, he bequeathed the residue of his considerable estate to three Buffalo institutions for the care of crippled, blind and needy children.

"Michael's research activities were prodigious and remarkably prolonged. The first of his 225 separate articles describing his researches was published when he was twenty-three years old; the last appeared a few months after his death sixty-six years later. It would be idle to attempt to recapitulate these many contributions; a few may be mentioned for which he will be particularly remembered.

"Michael was the first to synthesize a natural glucoside (hélicin, 1879), and the method that he introduced has become the standard synthetic route to this important class of compounds. Another landmark was his discovery, in 1887, of the addition of active-hydrogen reagents to α,β-unsaturated esters and carbonyl compounds; this, the Michael reaction, proved capable of wide elaboration and, in one or another of many modifications, constitutes an important tool of the modern builder of molecules. Another general synthetic method discovered by Michael, a modification of the Perkin Reaction, is extensively used for the condensation of aldehydes and malonic acid (1883). Finally may be mentioned his discovery of chlorine heptoxide, in 1900.

"This enumeration might seem to imply that Michael was concerned chiefly with the experimental rather than the theoretical aspects of chemistry. Actually the very opposite was the case. Michael was passionately interested in the theories of organic chemistry; that is, the fundamental laws and the mechanisms which might explain the marvelous variety and multiplicity of the compounds of carbon. All of his researches were undertaken to shed some light on these fundamental questions, and his numerous and far-ranging experimental investigations did, as a matter of fact, lead to the elaboration of a general theory of organic reactions. He developed special conceptions of the nature of valence, the condition of unsaturated systems, and the forces involved in chemical reactions, and he formulated a principle according to which 'every chemical system tends to so arrange itself that the maximum of chemical neutralization is attained.'

"While a few of Michael's collaborators learned to apply his method of reasoning, the Michaelian theories have had but little following, even though accorded the prominence of a special chapter in F. Henrich's treatise on the *Theories of Organic Chemistry*. Nevertheless, Michael himself, with his keen intuitive faculty, his wide experience in the laboratory, and his vast knowledge of the literature, could apply these concepts with extraordinary success both in the interpretation of known phenomena and in the prediction of unexplored happenings. Theories that can be thus applied certainly have a *prima facie* justification.

"The vigor of Michael's interest in theory and his extreme independence of thought were responsible for another important function which he performed throughout his long career to the great advantage of chemical science, namely, that of a sharp and penetrating critic of accepted views.

"When the van't Hoff theory of geometrical isomerism was gaining general acceptance through the able exploitation of Wislicenus and others, Michael flatly refused to accept what to him was an unproved hypothesis. Alert to any opportunity to attack current doctrine, he saw the weakness in Wislicenus' assumption that additions to unsaturated substances necessarily proceed in the *cis* direction and, in a series of carefully planned experiments, proved conclusively that *trans* addition does indeed occur. He thereby corrected an erroneous feature of this theory, but far from overthrowing the basic theory itself, his work extended and greatly strengthened a general concept that soon became a fully established tenet of the science. This example can be amplified by many others. Victor Meyer's view that the sulfone grouping is not comparable with the carbonyl and other acid-forming radicals was generally accepted until Michael (1889) succeeded in demonstrating the reactivity of the methylene groups in β-sulfonyl esters. Michael was the first to question the C-metal formulation of the metal derivatives of nitroparaffins (1888), and, in 1908, he challenged Claisen's views with regard to the relative stabilities of enolates. In 1920 he severely criticized Tiffeneau's interpretation of the pinacol and benzilic acid rearrangements, and, in 1935, he attacked the experimental basis for analogies accepted over a period of years as supporting the hypothetical addition–elimination mechanism of aromatic substitutions. His own astutely planned and faultlessly executed reinvestigations of the nitration and sulfonation of olefins proved the previously accepted analogies to be nonexistent, and indeed the hypothesis that he contested is now discarded.

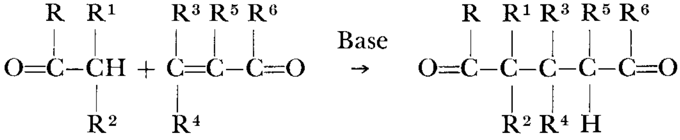
"Summarizing, we can say that Michael was a powerful theorist, a keen critic and a consummate experimentalist. Or perhaps with equal appropriateness we can in conclusion quote the citation opposite his name in *American Men of Science* describing his field of activity, which reads, "Investigations in organic chemistry bearing on its fundamental laws and theory."

In a review of the Michael reaction published 112 years after the initial discovery, E. D. Bergmann, D. Ginsburg, and R. Pappo* cite 1045 references to its exploration and use. They note that in its original scope the condensation is a base-catalyzed addition of an addend or donor (A) containing an α-hydrogen atom in the system O=C–CH to a carbon-carbon double bond that forms part of a conjugated system of the general formula-

---

* E. D. Bergmann, D. Ginsburg, and R. Pappo, "The Michael Reaction," *Organic Reactions* 10(1959):179.

tion C=C–C=O in an acceptor (B). Typical acceptors are α,β-unsaturated aldehydes, ketones, and acid derivatives. All



$$O{=}\overset{R}{C}-\underset{R^2}{\overset{R^1}{C}}H + \underset{R^4}{\overset{R^3}{C}}{=}\overset{R^5}{C}-\overset{R^6}{C}{=}O \xrightarrow{\text{Base}} O{=}\overset{R}{C}-\underset{R^2}{\overset{R^1}{C}}-\underset{R^4}{\overset{R^3}{C}}-\underset{H}{\overset{R^5}{C}}-\overset{R^6}{C}{=}O$$

A B

structures containing O=C–CH– in which the hydrogen is active by the Zerewitinoff test will serve as donors in the Michael reaction. In addition, many compounds that do not meet this test of hydrogen activity, such as acetophenone, are effective Michael reactants. Typical acceptors are α,β-unsaturated aldehydes, ketones, and acid derivatives. By extension of the original scope, the Michael reaction has come to be understood to include addends and acceptors activated by groups other than carbonyl and carboalkoxyl. The wider scope includes as donors nitriles, nitro compounds, sulfones, and certain hydrocarbons such as cyclopentadiene, indene, and fluorene that contain sufficiently reactive hydrogen atoms. Another hydrocarbon acceptor is the conjugated tetraacetylenic compound (I), which adds diethyl sodium malonate as follows:

$$\underset{\text{(I)}}{CH_3C\equiv C-C\equiv C-C\equiv C-C\equiv CCH_3} + CH_2(CO_2C_2H_5)_2 \xrightarrow{\text{Base}}$$

$$CH_3C\equiv C-C\equiv C-C\equiv C-CH{=}C(CH_3)CH(CO_2C_2H_5)_2$$

The review article cited discusses the mechanism of the Michael reaction, the nature of the anion of the adduct, and the reverse, or retrograde Michael reaction, used for example in establishing the course of the biosynthesis of cholesterol, the question of *para*-bridged intermediates, the stereochemistry of the Michael condensation, and related topics. In presenting a brief sketch of "an almost legendary figure, one of those giants of the days of the dawn of organic chemistry," W. T. Read * described Michael as "one of the most interesting figures that has ever appeared in the scientific world." In another review † Professor Albert B. Costa, historian of science of Duquesne University with research interests in nineteenth-century organic chemistry, described Michael's synthesis of natural glucosides and noted his preparation of pyrimidines by the reaction of ureas or thioureas with ethyl sodiomalonate. However, he states:

"Michael's primary concern was not these experimental contributions but organic theory. So concerned was he with fundamental principles that he elaborated a general interpretation of organic reactions and developed his own conceptions of the forces involved in chemical phenomena.‡ Energy conversions were for him the important controlling factors in all chemical changes, and he interpreted organic reactions in terms of energy in a long series of papers from 1888 on. His novel contribution to chemical theory was to introduce the thermodynamic conceptions of free energy and entropy into organic structural theory in order to overcome the pictorial and mechanical interpretation of chemical behavior.

"Michael's speculations included the genesis of the chemical elements in energetic terms (1910). The original corpuscles of matter were exclusively carriers of free chemical energy (convertible into less active chemical and physical energy), and all of the bound chemical energy (only partially reconvertible into free energy) appeared gradually in time from this original reservoir of free energy. Adopting the chemical evolutionary

---

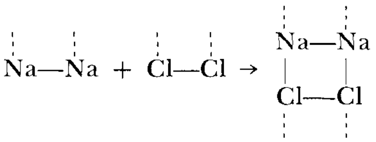
* W. T. Read, "American Contemporaries; Arthur Michael," *Industrial and Engineering Chemistry* 22(1930):1137.

† A. B. Costa, "Arthur Michael (1853–1942). Meeting of Thermodynamics and Organic Chemistry," *Journal of Chemical Education* 48(1971):243.

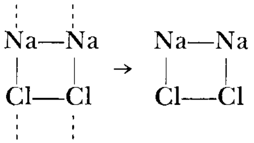
‡ F. Henrich, *Theories of Organic Chemistry*, transl. T. B. Johnson and D. A. Hahn (New York: John Wiley & Sons, Inc., 1922).

ideas then in vogue, he argued that the elements appeared in sequential order. In the earlier stages of the formation of the atoms of the elements the free energy of the original corpuscles was converted largely into bound energy and heat; thus, the atoms of the less active elements were formed. As the temperature rose in the process of chemical evolution, such extensive conversions of free into bound energy did not occur and more reactive elements gradually emerged. With the genesis of the radioactive elements there appeared atoms with so much free energy that they were unstable.

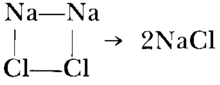
"Having the chemical elements with their varying degrees of activity based on their free energy content, Michael set out to interpret chemical reactions. His starting point was Kekulé's idea that the first stage in every chemical reaction consisted in two molecules attracting each other through their chemical affinity to form a double molecule. Michael proposed that the free chemical energy in two unlike molecules was converted in part into bound energy and heat, the stability of the double molecule being determined by the extent of this conversion. He represented the reaction between sodium and chlorine in the following manner, using dotted lines to represent the free energy and solid lines the bound energy of atoms.



$$\overset{\vdots}{\mathrm{Na}}-\overset{\vdots}{\mathrm{Na}}+\overset{\vdots}{\mathrm{Cl}}-\overset{\vdots}{\mathrm{Cl}}\rightarrow\begin{array}{ccc}\vdots&&\vdots\\ \mathrm{Na}&-&\mathrm{Na}\\ |&&|\\ \mathrm{Cl}&-&\mathrm{Cl}\\ \vdots&&\vdots\end{array}\qquad(1)$$



$$\begin{array}{ccc}\vdots&&\vdots\\ \mathrm{Na}&-&\mathrm{Na}\\ |&&|\\ \mathrm{Cl}&-&\mathrm{Cl}\\ \vdots&&\vdots\end{array}\rightarrow\begin{array}{ccc}\mathrm{Na}&-&\mathrm{Na}\\ |&&|\\ \mathrm{Cl}&-&\mathrm{Cl}\end{array}\qquad(2)$$



$$\begin{array}{ccc}\mathrm{Na}&-&\mathrm{Na}\\ |&&|\\ \mathrm{Cl}&-&\mathrm{Cl}\end{array}\rightarrow 2\mathrm{NaCl}\qquad(3)$$

"In phase (1) the free energy in sodium and chlorine molecules resulted in the formation of a double molecule of the elements. Phase (2) represented the neutralization of the free energy as completely as possible. Finally, the bound energy between the two sodium atoms and two chlorine atoms was converted into bound energy between sodium and chlorine, the energy of the like atoms not being sufficient to hold these atoms together.

"In general, every spontaneous chemical change involved the conversion of free into bound energy. Every atom represented a definite quantity of potential chemical energy and had a tendency toward a condition of greater stability. Free energy and the affinity relationships of the atoms determined the chemical potential of a system.

"To Michael, the second law of thermodynamics was the most firmly established generalization in science. The increase in entropy that took place in every spontaneous chemical change must be the soundest basis for organic theory. For entropy, he substituted 'chemical neutralization,' meaning by this the neutralization of the free energy of the reacting atoms. The greater the conversion of free into bound energy that took place the more the neutralization of the chemical forces of the atoms. He then restated the second law in chemical terms: 'Every chemical system tends to arrange itself so that the maximum of chemical neutralization is attained.'

"Michael applied this general theory in detail to organic chemistry. Molecular rearrangements, addition and substitution reactions, tautomerism, and stereochemical phenomena were among the aspects of organic chemistry included within his theory. In the case of molecular rearrangements he proposed four factors which determined whether rearrangements might occur: (1) the extent of free energy among the interchanging atoms or groups; (2) their affinity for each other and for the atoms in the group to which they migrate; (3) the amount of energy required to separate migrating parts from the remaining part of the molecule; and (4) the heats of formation of the substances. He related these factors to the structures of the substances involved and explained a variety of rearrangement reactions, all of which entailed an increase in entropy, or in his terms, a neutralization of surplus free energy. A rearrangement might occur if a well neutralized substance was formed, provided that the increase in entropy due to the intramolecular neutralization was greater than the decrease in entropy due to factor (3).

"Michael's account of the tautomerism of nitromethane and nitrosomethane is an interesting example of the application of his ideas. Nitrosomethane (CH_3NO) is unstable and spontaneously forms the oxime ($CH_2{:}N\cdot OH$), whereas nitromethane (CH_3NO_2) is stable and its tautomer ($CH_2{:}NO\cdot OH$) is relatively unstable. He noted that the nitroso group has more free energy than the nitro group, the latter having the higher heat of formation. In nitrosomethane the oxygen has a strong affinity for the hydrogen of the methyl group. By changing into the oxime, much of the free energy in the nitroso group is converted into bound energy and heat; hence, there has been formed a well neutralized substance. However, the nitro group has less free energy, and its oxygen is less capable of overcoming the bound energy holding the hydrogen to carbon in the methyl group. Furthermore, nitromethane is poorer in free energy than the strongly acidic tautomer; hence, a rearrangement would result in a decrease in entropy and would not be favored.

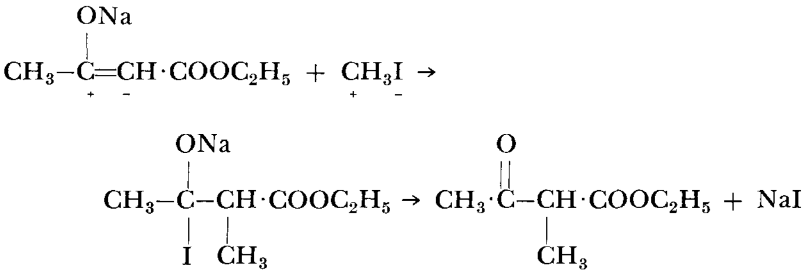
"After the proof that tautomerism was the result of a mobile equilibrium between *keto* and *enol* forms, Michael investigated the conditions of stability of the forms and showed that the phenomena depended on the energy, affinity, and entropy relations of the tautomers and the solvent. He proposed an interaction between solvent and solute molecules: *Keto*-Solvent $\rightleftharpoons$ *Enol*-Solvent. If the transformation was accomplished by an increase in entropy, tautomerization resulted with that particular solvent, the degree of tautomerization depending on the relative increase in entropy. With a large difference, only one form was stable; a small difference meant that both forms were stable.

"Michael concentrated much of his work on the theoretical aspects of addition to the double bond and the behavior of active methylene compounds. He claimed that addition reactions played a much more important role than chemists hitherto believed, and that many substitution reactions involved additions as a preliminary stage. A substitution was more often than not the end result of an addition followed by an elimination reaction. His interpretation of the mechanism of reactions according to an addition with the formation of an intermediate 'addition product' proved to be an important concept.

"The addition process meant that a substance was unsaturated, and unsaturated compounds have free energy potentially convertible into bound energy. His understanding of unsaturation in organic compounds was a consistent aspect of his general theory. By removal of a hydrogen atom from each carbon atom in ethane, the energy used to hold these hydrogen atoms was now employed in increasing the self-saturation of the carbon atoms. Hence, ethylene is a storehouse of potential chemical energy.

"Michael published many papers on the addition of unsymmetric addenda to unsymmetric unsaturated compounds. He proposed a 'positive–negative' rule as a way of determining the course of such addition reactions: the maximum neutralization is attained by the electronegative atom or group of the addendum combining with the more electropositive atom of the unsaturated molecule and the more electropositive atom or group to the more electronegative atom of the molecule. In propene ($CH_3CH{:}CH_2$), e.g., the positive methyl radical made the central carbon more positive than the end carbon atom. Hence, hydrogen iodide (H^+I^-) added to form mainly the secondary iodide (CH_3CHICH_3), although a small amount of primary iodide was also formed in agreement with Michael's distribution principle (see below). The addition of ICl and BrCl gave different results. ICl (I^+Cl^-) added to form mainly the primary iodide. Michael found experimentally that the isomeric addition products were present in a ratio of 3:1 of the primary to the secondary iodide. With BrCl the two atoms were more nearly equal in electronegativity and more nearly equal amounts of the primary and secondary bromide were formed. (He obtained them in a 7:5 ratio.) These relations were consistent with the energetic character of the compounds. In the addition of hydrogen iodide to propene the maximum entropy increase was realized in the formation of the secondary iodide; it has a greater heat of formation than the primary compound and thus a greater neutralization within the molecule.

"The positive–negative rule also clarified Michael's malonic and acetoacetic ester syntheses. These too were instances of heterogeneous addition. Both ethyl sodioacetoacetate and methyl iodide had pronounced positive–negative properties. Their reaction involved the separation of iodine from the methyl group, the attraction of sodium for iodine compared to the attraction of sodium for oxygen, and the attraction of methyl for one of the unsaturated atoms in the ester. The methyl would tend to combine with the most negative of the unsaturated atoms. The positive metal directed the course of reaction



$$CH_3-\underset{+}{\overset{ONa}{C}}=\underset{-}{CH}\cdot COOC_2H_5 + \underset{+}{CH_3}\underset{-}{I} \rightarrow$$

$$CH_3-\underset{I}{\overset{ONa}{C}}-\underset{CH_3}{CH}\cdot COOC_2H_5 \rightarrow CH_3\cdot\overset{\overset{O}{\|}}{C}-\underset{CH_3}{CH}\cdot COOC_2H_5 + NaI$$

"Michael found experimentally that if the metal was less positive and the addendum more negative, e.g., silver acetoacetate and acyl iodide, then the affinity relations were changed. The affinity to methyl was diminished more than that of metal to oxygen and the tendency of the reaction was toward substitution, not addition. Silver acetoacetate and methyl iodide still produced a methylated compound, but in decreased yield. If an acyl iodide was substituted for methyl iodide, substitution took place instead of addition, the acidic group attaching to oxygen. The positive and negative groups of both components distributed themselves to produce the maximum neutralization of affinities.

"Since all reactions do not produce one set of products, Michael introduced his 'distribution principle': 'If two unsaturated atoms A and B are present in a molecule which exhibits unequal affinity towards C and D of the addendum CD, and if A has greater affinity for C than has B, addition will occur if the affinity of AC–BD is greater than that of CD, and the more readily and completely the larger the difference. In this process of addition not only the affinity of A to C and of B to D comes into action, but also that of A to D and B to C, and therefore the further possibility is presented, not only of the combination of AC–BD, but of AD–BC, and the latter in increasing proportion the nearer the two combinations AC–BD is greater than AD–BC approach one another.' Thus, the more closely two atoms of a molecule resemble each other in chemical affinity for a third, the more nearly equal will be the relative number of molecules of the two compounds formed.

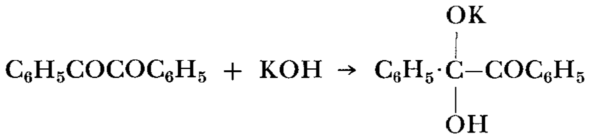
"Another important contribution, perhaps as important as his thermodynamic theory in its direct influence on organic chemists, was Michael's role as a critic. He responsibly throughout his long career was a sharp and penetrating critic of accepted views. When the theory of geometrical isomerism was gaining acceptance through the work of Wislicenus and others, he refused to accept what was to him the unjustified assumption that additions to unsaturated compounds always proceeded with the formation of cis products and that eliminations occurred more easily with cis than with trans isomers. In a series of carefully planned experiments Michael proved conclusively that trans additions did occur and that all of the then adopted configurations of geometric isomers were erroneous. He proved that fumaric acid derivatives were the direct products of the addition of halogens and hydrohalic acids to acetylenic acids and that the fumaric configurations of halo-succinic acids lost HX or halogen more readily than the isomeric compounds with the maleic acid configuration. He argued that both cis and trans additions and eliminations may occur in a given case to yield a mixture of isomers whose relative proportions depended on conditions incompatible with any mechanical conception of the process.

"Far from overthrowing the basic theory, Michael felt that his correction of it greatly strengthened stereochemistry and ensured that it would become a fully established part of organic chemistry. Where chemists such as Wislicenus had erred was in thinking that the stereochemical course of reactions could be represented by purely mechanical, geometric means; adequate understanding required the use of thermodynamic factors.

"Another example of his penetrating criticism was his reinterpretation of several types of rearrangements, as illustrated by his examination of the benzilic acid rearrangement

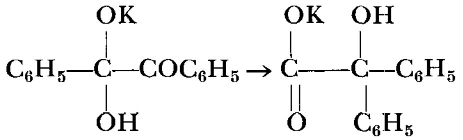
$$C_6H_5COCOC_6H_5 \xrightarrow{KOH} (C_6H_5)_2C(OH)COOK$$

He studied the explanations of the rearrangement of benzil into benzilic acid put forth by Nef and by Tiffeneau and found them to be chemically impossible. Tiffeneau, e.g., proposed the addition of an alkali molecule to each carbonyl group, followed by the elimination of water and isomerization to dipotassium benzilate. Michael pointed out that there was no experimental evidence that benzil could add two molecules of alkali or that benzilic acid formed a dibasic salt. His explanation was in terms of affinity and energy: the affinity of the carbon atoms of the two carbonyl groups in benzil was greatly decreased by the attached oxygen atoms, and the compound was easily ruptured at that point. But in the presence of alkali the following reaction took place



$$C_6H_5COCOC_6H_5 + KOH \rightarrow C_6H_5\cdot\underset{\textstyle OH}{\overset{\textstyle OK}{C}}-COC_6H_5$$

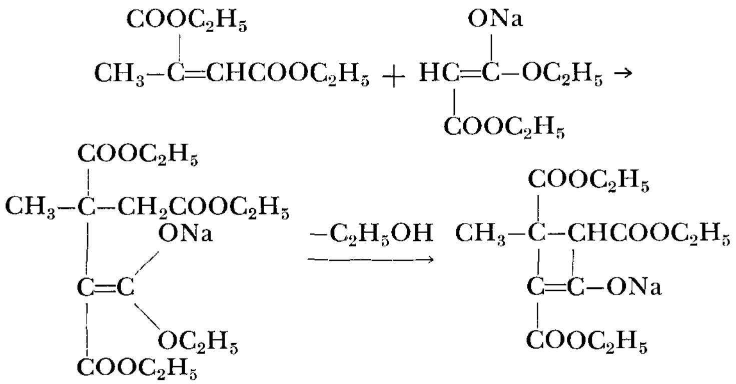
The alkali greatly increased the amount of energy needed to rupture the carbon–carbon bond, while decreasing the amount of energy needed to break the bond between the phenyl group and the newly saturated carbon atom. Thus, a change in affinity relations had occurred, and the system, instead of rupturing a carbon–carbon bond, was converted by migration of the phenyl group and a hydrogen atom into a salt of benzilic acid with a large increase in entropy



$$C_6H_5-\underset{\textstyle OH}{\overset{\textstyle OK}{C}}-COC_6H_5 \rightarrow \underset{\textstyle O}{\overset{\textstyle OK}{C}}-\!\!-\underset{\textstyle C_6H_5}{\overset{\textstyle OH}{C}}-C_6H_5$$

"Michael was a critic of all purely mechanical interpretations of organic reactions, such as Victor Meyer's steric hindrance concept and Baeyer's strain hypothesis. He experimentally showed that steric hindrance was very limited and was applicable to the esterification of substituted benzoic acids only when hydrochloric acid was used as a catalyst. He demonstrated that the formation of esters of such acids without this catalyst proceeded as smoothly as with other organic acids.

"Baeyer explained the ready formation and stability of five- and six-membered rings by postulating that the ease of formation of a ring depended on the amount a bond must deviate from the tetrahedral angle of 109°28′ in order to form the bond. Since the strain hypothesis did not consider the chemical affinity and energy relations nor the influence of side groups, it could not be for Michael a comprehensive explanation of ring formation. He proved experimentally that with certain side groups cyclobutyl derivatives were as easily formed as any derivatives of five- or six-membered rings. He prepared a four-membered ring compound by the addition of ethyl sodiomalonate to ethyl citraconate



To Michael, the strain hypothesis required significant modification before it could offer a satisfactory explanation of ring formation.

"Michael's speculations were an attempt to broaden and develop structural theory in organic chemistry. Structural theory was too mechanical and the attempts to remedy its defects were always along mechanical lines, such as conceptions of new kinds of valencies (partial, dissociated), oxonium and carbonium theories, steric hindrance, etc. All of these were inadequate to the challenge, for they all failed to consider energy–affinity relations. For Michael, all the forces in nature had the same end: the realization of the maximum increase in entropy, and a sound chemcial theory must have this fundamental law as a basis. He stressed the need for thermochemical and physico–chemical investigations in order to reveal the intimate connection between energy relations and chemical behavior and hoped that the union of thermodynamical principles with structural theory would lead to a more profound science of organic chemistry. His Harvard colleagues, in summarizing his contribution to chemistry, referred to him as 'a powerful theorist, a keen critic and a consummate experimentalist.' "

BIBLIOGRAPHY

KEY TO ABBREVIATIONS

Am. Chem. J. = American Chemical Journal
Ber. dtsch. chem. Ges. = Berichte der deutschen chemischen Gesellschaft
J. Am. Chem. Soc. = Journal of the American Chemical Society
J. Org. Chem. = Journal of Organic Chemistry
J. prakt. Chem. = Journal für praktische Chemie
Ann. Chem. = Justus Liebigs Annalen der Chemie

1876

Über die Einwirkung von Kaliumsulphhydrat auf Chloralhydrat. Ber. dtsch. chem. Ges., 9:1267.

With T. H. Norton. Über die Darstellung und Eigenschaften des Trijodresorcins. Ber. dtsch. chem. Ges., 9:1752.

1877

With S. Gabriel. Über die Einwirkung von wasserentziehenden Mitteln auf Säureanhydride. Ber. dtsch. chem. Ges., 10:391.

Zur Darstellung der Paramidobenzoësäure. Ber. dtsch. chem. Ges., 10:576.

With T. H. Norton. Über die Diamidosulphobenziddicarbonsäure. Ber. dtsch. chem. Ges., 10:580.

With A. Adair. Zur Kenntniss der aromatischen Sulphone. Ber. dtsch. chem. Ges., 10:583.

Über die Einwirkung des Broms auf Aethylphtalimid. Ber. dtsch. chem. Ges., 10:1644.

1878

With L. M. Norton. Über die Einwirkung des Chlorjodes auf aromatische Amine. Ber. dtsch. chem. Ges., 11:107.

With A. Adair. Zur Kenntniss der aromatischen Sulphone. Ber. dtsch. chem. Ges., 11:116.

1879

Über die Synthese des Phenolglykosides und des Orthoformylphenolglykosides oder Helicins. Comptes rendus hebdomadaires des séances de l'academie des sciences, 89:355; also in Ber. dtsch. chem. Ges., 12:2260; Am. Chem. J., 1:305.

With A. Kopp. Einwirkung verschidener Salzen auf Aldehyd Versuche angestellt. Ber. dtsch. chem. Ges., 12:2091.

On a new formation of stilbene and some of its derivatives. Am. Chem. J., 1:312; also in J. Am. Chem. Soc., 2:42 (1880).

Laboratory Notes. I. On mono-ethylphthalate. Am. Chem. J., 1:413; also in Ber. dtsch. chem. Ges., 13:1873 (1880); J. Am. Chem. Soc., 2:220 (1880).

Laboratory Notes. II. On a new formation of ethyl-mustard oil. Am. Chem. J., 1:416; also in J. Am. Chem. Soc., 2:221 (1880).

Laboratory Notes. III. On the preparation of methyl aldehyde. Am. Chem. J., 1:418; also in Ber. dtsch. chem. Ges., 13:1864 (1880); J. Am. Chem. Soc., 2:221 (1880).

Laboratory Notes. IV. On the "migration of atoms in the molecule" and Reimer's chloroform aldehyde reaction. Am. Chem. J., 1:420.

1880

Aethylsenfölbildung. Ber. dtsch. chem. Ges., 13:1866.

With L. M. Norton. On α- and β-monobromcrotonic acids. Am. Chem. J., 2:11.

With C. Gundelach. Preliminary note on the synthesis of methylconine and constitution of conine. Am. Chem. J., 2:171.

Darstellung von Methylaldehyd. J. Am. Chem. Soc., 2:221.

1881

With C. Gundelach. Vorläufige Notiz über die Synthese des Methylconiins und die Constitution des Coniins. Ber. dtsch. chem. Ges., 14:110.

Über die Einwirkung von aromatischen Oxysäuren auf Phenole. Ber. dtsch. chem. Ges., 14:656.

With L. M. Norton. Über α- und β-Monobromcrotonsäure. Ber. dtsch. chem. Ges., 14:1202.

Über die Synthese des Methylarbutins. Ber. dtsch. chem. Ges., 14:2097.

Zur Kenntniss des *p*-Coniins. Ber. dtsch. chem. Ges., 14:2105.

1882

Über die Synthese des Salicins und des Anhydrosalicylglucosids. Ber. dtsch. chem. Ges., 15:1922.

1883

On the action of aromatic oxy-acids on phenols. Am. Chem. J., 5:81; also in Ber. dtsch. chem. Ges., 16:2298.

With A. M. Comey. On some properties of phenylsulphonacetic ethers. Am. Chem. J., 5:116; also in Ber. dtsch. chem. Ges., 16:2300.

Synthetical researches in the glucoside group. Am. Chem. J., 5:171.

With A. Kopp. On the formation of crotonic and β-oxybutyric aldehydes from ethyl aldehyde. Am. Chem. J., 5:182; also in Ber. dtsch. chem. Ges., 16:2501.

Laboratory Notes. V. On the action of sodium ethyl oxide on bromethylidenebromide. Am. Chem. J., 5:192; also in Ber. dtsch. chem. Ges., 16:2499.

Laboratory Notes. VI. A new synthesis of allantoin and some suggestions on the constitution of uric acid. Am. Chem. J., 5:198; also in Ber. dtsch. chem. Ges., 16:2506.

Laboratory Notes. VII. On a convenient method for preparing bromacetic acid. Am. Chem. J., 5:202; also in Ber. dtsch. chem. Ges., 16:2502.

Laboratory Notes. VIII. On several cases of intermolecular rearrangement. Am. Chem. J., 5:203.

Laboratory Notes. IX. On a new synthesis of cinnamic acid. Am. Chem. J., 5:205.

With A. M. Comey. On the action of aldehydes on phenols. II. Am. Chem. J., 5:349.

Laboratory Notes. X. Some convenient quantitative lecture apparatus. Am. Chem J., 5:353.

Laboratory Notes. XI. Observations on the action of acetylchloride and acetic anhydride on corn and wheat starch. Am. Chem. J., 5:359.

On the constitution of resocyanin. Am. Chem. J., 5:434.

1884

With G. M. Palmer. On the action of sodium phenylsulphinate on methylene iodide. Am. Chem. J., 6:253.

With G. M. Palmer. On the conversion of organic isocyanates into mustard oils. Am. Chem. J., 6:257.

Synthetical researches in the glucoside group. III. Am. Chem. J., 6:336.

With J. F. Wing. On the action of methyl iodide on asparagine. Am. Chem. J., 6:419.

1885

With G. M. Palmer. On some properties of phenylsulphonacetic ethers. II. Am. Chem. J., 7:65.

With J. F. Wing. Note on the constitution of the addition-product of chlorhydric acid to ethylcyanide. Am. Chem. J., 7:71.

On the decomposition of cinchonine by sodium ethylate. Am. Chem. J., 7:182.

With G. M. Palmer. On simultaneous oxidation and reduction by means of hydrocyanic acid. Am. Chem. J., 7:189.

With J. F. Wing. On the action of alkyl iodides on amido acids. Am. Chem. J., 7:195.

With G. M. Palmer. On resacetophenone. Am. Chem. J., 7:275.

With J. F. Wing. On inactive aspartic acid. Am. Chem. J., 7:278.

1886

Über einen Zusammenhang zwischen Anilidbildung und der Constitution ungesättigter, mehrbasischer, organischer Säuren. Ber. dtsch. chem. Ges., 19:1372.

With G. M. Palmer. Über einen Zusammenhang zwischen Anilidbildung und der Constitution ungesättigter, Mehrbasischer, organischer Säuren. II. Ber. dtsch. chem. Ges., 19:1375.

Über die einwirkung des Anilins auf die Brommalein- und Chlorfumarsäure. Ber. dtsch. chem. Ges., 19:1377.

With G. M. Browne. Zue Isomerie in der Zimmtsäurereihe. Ber. dtsch. chem. Ges., 19:1378.

Zue isomerie in der Fettreihe. Ber. dtsch. chem. Ges., 19:1381.

Über die Nitrirung des Phenylhydrazins. Ber. dtsch. chem. Ges., 19:1386.

With J. P. Ryder. Zur Kenntniss der Einwirkung von Aldehyden auf Phenole. Ber. dtsch. chem. Ges., 19:1388.

Die Citraconsäure als Reagenz zur Erkennung und Scheidung der Aromatischen Amine. Ber. dtsch. chem. Ges., 19:1390.

With G. M. Browne. Überführung der α-Bromzimmtäther in Benzoylessigäther. Ber. dtsch. chem. Ges., 19:1392.

Einwirkung von Phosphorpentachlorid auf einige organische Ver-

bindungen. Gesellschaft deutscher Naturforscher und Arzte. Tageblatt Naturforsch-Versammlung zu Berlin, 411.

1887

Über eine bequeme Darstellungsweise von bromirten Fettsäuren. J. prakt. Chem., 35:92.

Das Verhalten von Essigsäure und einigen Derivaten derselben gegen Fünffach-chlorphosphor. J. prakt. Chem., 35:95.

Über die Constitution der Trimethylentricarbonsäure. J. prakt. Chem., 35:132.

Über die Bildung des Indigblau aus Orthonitrophenylpropiolsäure mittelst Cyankalium. J. prakt. Chem., 35:254.

With G. M. Browne. Über alloisomerie in der Crotonsäurereihe. J. prakt. Chem., 35:257.

Über die Addition von Natriumacetessig- und Natriummalonsäureather zu den Äthern ungesättigter Säuren. J. prakt. Chem., 35:349; also in Am. Chem. J., 9:112.

Die Reduction von alpha- und alloalphabromzimmtsäuren zu Zimmtsäure. J. prakt. Chem., 35:357.

With G. M. Browne. Über aromatische Hydroxylamine. J. prakt. Chem., 35:358.

On some new reactions with sodium acetacetic and sodium malonic ethers. Am. Chem. J., 9:124; also in J. prakt. Chem., 35:449.

With J. P. Ryder. On the action of aldehydes on phenols. III. Am. Chem. J., 9:130.

Über das Verhalten von Oxalsäureäther zu Resorcin. J. prakt. Chem., 35:510.

Bemerkungen zu einer Abhandlung des Hrn. L. Claisen. Ber. dtsch. chem. Ges., 20:1572.

Researches on alloisomerism. I. A relation between the constitution of polybasic unsaturated organic acids and the formation of their anilides. Am. Chem. J., 9:180.

With G. M. Palmer. Researches on alloisomerism. II. Am. Chem. J., 9:197.

On the action of phosphorus pentachloride on the ethers of organic acids, and on some derivatives of acetic acid. Am. Chem. J., 9:205.

On the action of phosphorus pentachloride on acetanilide. Am. Chem. J., 9:217; also in J. prakt. Chem. 35:207.

Preliminary notes. Am. Chem. J., 9:219.

Antwort auf eine Bemerkung von L. Claisen. J. prakt. Chem., 36:113.

With G. M. Browne. Researches on alloisomerism. Am. Chem. J., 9:274.

With G. M. Browne. Zur isomerie in der Crotonsäurereihe. J. prakt. Chem., 36:174.

Remarks on the constitution of levulinic and maleic acids. Am. Chem. J., 9:364.

1888

Preliminary notes on the constitution of sodium acetacetic and malonic esters. Am. Chem. J., 10:158.

Über das verhalten von Natriummalonäther gegen Resorcinol. J. prakt. Chem., 37:469.

Zur constitution des Natriumacetessigäther. J. prakt. Chem., 37:473.

With H. Pendleton. Zur Alloisomerie in der Krotonsäurereihe. J. prakt. Chem., 38:1.

Zur kritik der Abhandlung von J. Wislicenus: "Über die räumliche Anordung der Atome in organischen Molekulen." J. prakt. Chem., 38:6.

1889

Bemerkung zu der Abhandlung von J. Wislicenus: "Zur geometrischen Constitution der Krotonsäuren und ihrer Halogensubstitutionsprodukte." J. prakt. Chem., 40:29.

With H. Pendleton. Zu Alloisomerie in der Zimmtsäurereihe. J. prakt. Chem., 40:63.

With P. Freer. Über die einwirkung von Jodwasserstoffsäure auf die Krotonsäuren. J. prakt. Chem., 40:95.

Über die Regelmässigkeiten bei der Anlagerung von Halogenverbindungen an ungesättigte Säuren. J. prakt. Chem., 40:171.

1890

Bemerkung zu der Abhandlung von Otto und Rossing über die Ersetzbarkeit des Natriums in Natriumphenylsulfonessigäther durch Alkyle. Ber. dtsch. chem. Ges., 23:669.

Bemerkungen zu der Abhandlung von Goldschmidt und Meissler über "Versuche zur Constitutionsbestimmung tautomerer Verbindungen." J. prakt. Chem., 42:19.

1891

With P. C. Freer. Über die Addition von Natriumacetessig- und Natriummalonsäther zu den Äthern ungesättigter Säuren. II. J. prakt. Chem., 43:390.

With O. Schulthess. Untersuchungen über Alloisomerie. I. Zur Kenntnis der Halogenentziehung bei organischen α-β-Halogensäureäthern. J. prakt. Chem., 43:587.

Zur Kenntnis der Lävulinsäure und des Acetondiessigsäuredilaktons. J. prakt. Chem., 44:113.

Bemerkung zu der Abhandlung von Ad. Claus: über die Umsetzung von Dibrombernsteinsäureester mit Zink. J. prakt. Chem., 44:399.

With G. Tissot. Zur Kenntnis der Homologen der Äpfelsäure. Ber. dtsch. chem. Ges., 24:2544.

1892

On the constitution of sodium acet-acetic ether. Am. Chem. J., 14:481.

With O. Schulthess. Über die Addition von Natriumacetessig- und Natriummalonsäureäther zu den Äthern ungesättigter Säuren. J. prakt. Chem., 45:55.

Zur Konstitution des Natriumacetessigäther. J. prakt. Chem., 45:580; 46:189.

Untersuchungen über Alloisomerie. II. Tul. I. Über die Addition von Brom zu Acetylendicarbonsäure und deren Äthyläther. J. prakt. Chem., 46:209.

With C. C. Maisch. Über die Einwirkung von Natriumäthylat auf Dibrombernsteinsäureäther. J. prakt. Chem., 46:233.

With O. Schulthess. Untersuchungen über Alloisomerie. II. III. Über die Crotonsäure und Derivate derselben. J. prakt. Chem., 46:236.

Untersuchungen über Alloisomerie. II. IV. Über die Bildung von fester Crotonsäure bei der Reduktion von allo-α-Brom- und -chlorcrotonsäure. J. prakt. Chem., 46:266.

With G. Tissot. Untersuchungen über Alloisomerie. II. VI. Beiträge zur Kenntniss einiger Homologen der Äpfelsäure. J. prakt. Chem., 46:285.

With G. Tissot. Untersuchungen über Alloisomerie. II. VII. Über

die Addition von Chlor zu mehrbasischen ungesättigten Fettsäuren. J. prakt. Chem., 46:381.

Untersuchungen über Alloisomerie. II. VIII. Vergleich der Versuchsergebnisse mit den theoretischen Folgerungen aus den Hypothesen Le Bel-Van't Hoff und Wislicenus. J. prakt. Chem., 46:400.

Untersuchungen über Alloisomerie. II. IX. Die van't Hoff'sche Hypothese in ihrer Anwendung auf die Gegenseitegen Beziehungen gesättigter und ungesättigter Fettsäuren. J. prakt. Chem., 46:424.

1893

Untersuchungen über Alloisomerie. J. prakt. Chem., 47:197.

Über die Einwirkung von Diazobenzolimid auf Acetylendicarbonsäuremethylester. J. prakt. Chem., 48:94.

1894

Über die Addition von Natriumacetessig- und Natriummalonsäureäther zu den Äthern ungesättigter Säuren. J. prakt. Chem., 49:20.

Beiträge zur Kenntnis des Ringbildung bei organischen, stickstoffhaltigen Verbindungen. J. prakt. Chem., 49:26.

Über die Einwirkung von Natriummalonäthylester auf Benzalaceton. Ber. dtsch. chem. Ges., 27:2126.

With G. Tissot. Über die Brommesakonsäure. Ber. dtsch. chem. Ges., 27:2130.

1895

Zur Schmelzpunktbestimmung von hochschmelzenden und sogenannten unschmelzbaren organischen Verbindungen. Ber. dtsch. chem. Ges., 28:1629.

Über die Addition von Schwefel zu ungesättigten organischen Verbindungen. Ber. dtsch. chem. Ges., 28:1633.

With J. E. Bucher. Über die Einwirkung von Essigsäureanhydrid auf Säuren der Acetylenreihe. Ber. dtsch. chem. Ges., 28:2511.

Untersuchungen über Alloisomerie. III. J. prakt. Chem., 52:289.

With T. H. Clark. Relative Leichtigkeit der Kohlendioxydabspaltung aus den Silversalzen der β-Chlorcrotonsäuren. J. prakt. Chem., 52:326.

With G. Tissot. Dritter abschnitt. J. prakt. Chem., 52:331.

Vierter abschnitt: über die gesetze der Alloisomerie und Anwendung derselben zur Classificirung ungesättigter organischer Verbindungen. J. prakt. Chem., 52:344.

Bemerkungen zu Arbeiten von C. A. Bischoff, J. A. Wislicenus and J. H. van't Hoff. J. prakt. Chem., 52:365.

1896

Über die Einwirkung von Äthyljodid und Zinc auf $\Delta^{\alpha,\beta}$-Fettester. Ber. dtsch. chem. Ges., 29:1791.

With J. E. Bucher. Zur Constitution der Oxalessigsäure. Ber. dtsch. chem. Ges., 29:1792.

Zur Kenntniss der Additionsvorgänge bei den Natriumderivaten von Formyl- und Acetessigestern und Nitroäthanen. Ber. dtsch. chem. Ges., 29:1793.

Herrn. E. Erlenmeyer und C. Liebermann zur Erwiderung. J. prakt. Chem., 54:107.

1898

With J. E. Bucher. On the action of acetic anhydride on phenylpropiolic acid. Am. Chem. J., 20:89.

With F. Luehn and H. H. Higbee. On the formation of imido-1,2-diazol derivative from aromatic azimides and esters of acetylenecarboxylic acids. Am. Chem. J., 20:377.

Über das Verhalten von Benzaldehyd gegen Phenol. J. prakt. Chem., 57:334.

1899

Über die Ersetzung des Natriums in Natriumphenylsulfonessigester durch Alkyle. J. prakt. Chem., 60:96.

Über einige Gesetze und deren Anwendung in der organischen Chemie. I. J. prakt. Chem., 60:286.

With V. L. Leighton. Über einige Gesetze und deren Anwendung in der organischen Chemie. II. J. prakt. Chem., 60:409.

With W. T. Conn. On chlorine heptoxide. Am. Chem. J., 23:444.

1900

Zur Kenntniss der Natriumacetessigestersynthese und der Vierringbildung mittels Natriumäthylats. Ber. dtsch. chem. Ges., 33:3731.

1901

With W. T. Conn. On the behavior of iodine and bromine toward chlorine heptoxide and perchloric acid. Am. Chem. J., 25:89.

Zur Kenntniss der Perkin'schen Reaction. Ber. dtsch. chem. Ges., 34:918.

On methyl cyanide as a catalytic reagent and a criticism of J. U. Nef's views on the Frankland-Wurtz- and Conrad reactions. Am. Chem. J., 25:419.

With V. L. Leighton and F. D. Wilson. Über die isomeren Isobutylenchlorhydrine und die Zersetzung der gemischten Äether durch Halogenwasserstoff. J. prakt. Chem., 64:102.

Zur Kenntniss der drei stereomeren Zimmtsäuren. Ber. dtsch. chem. Ges., 34:3640.

With W. W. Gerner and W. H. Graves. Zur Kenntniss der Substitution-vorgänge in der Fettreihe. Ber. dtsch. chem. Ges., 34:4028.

Über einige Laboratoriumsapparate. Ber. dtsch. chem. Ges., 34: 4058.

With T. H. Mighill. Zur Kenntniss des Additions-Abspaltungs-Gesetzes. Ber. dtsch. chem. Ges., 34:4215.

1903

Bemerkung zur der Mittheilung des Hrn. S. Svoboda "Über einen abnormalen Verlauf der Michael'schen Condensation." Ber. dtsch. chem. Ges., 36:763.

With W. W. Garner. Beiträge zur Frage der Isozmutsäure. Ber. dtsch. chem. Ges., 36:900.

Zur Geschichte der Isozimmtsäure. Ber. dtsch. chem. Ges., 36:2497.

On the condensation of oxalic ethylester with ethylene and trimethylene cyanides. Am. Chem. J., 30:156.

Valenzhypothesen und der Verlauf chemischer Vorgänge. J. prakt. Chem., 68:487.

With V. L. Leighton. Über die Konstitution des Phenylcinnamenylakrylsäuredibromids. J. prakt. Chem., 68:521.

1905

Phenylisocyanat als Reagens zur Feststellung der constitution tautomerer Verbindungen. Ber. dtsch. chem. Ges., 38:22.

With O. Eckstein. Über die Bildung von *o*-Acylderivaten aus Cyanessigester durch Anwendung von Pyridin und Chinolin. Ber. dtsch. chem. Ges., 38:50.

Zur Geschichte der Theorie über die Bildung und Constitution des Natracetessigesters. Ber. dtsch. chem. Ges., 38:1922.

Zur Kenntniss der Synthesen mit Natracetessigester. Ber. dtsch. chem. Ges., 38:2096.

Zur Frage über der Verlaug der Claisen'schen Zimmtsäureestersynthese. Ber. dtsch. chem. Ges., 38:2523.

Zur Kenntniss der Vorgänge bei der Synthesen mit Natrium Malonester und verwandten Verbindungen. Ber. dtsch. chem. Ges., 38:3217.

Herren Störmer und Kippe zur Erwiderung. Ber. dtsch. chem. Ges., 38:4137.

Über die Darstellung reiner Alkylmalonester. J. prakt. Chem., 72:537.

1906

On the isomerism and tautomerism question. Am. Chem. J., 35: 201.

With H. D. Smith and A. Murphy, Jr. The question of isomerism and tautomerism. Ber. dtsch. chem. Ges., 39:203.

Zur constitution des Tribenzoylenbenzols. Ber. dtsch. chem. Ges., 39:1908.

With W. W. Garner. Cinnamylideneacetic acid and some of its transformation products. Am. Chem. J., 35:258.

With W. W. Garner. Magnesium permanganate as an oxidizing agent. Am. Chem. J., 35:267.

Zur constitution des "Kohlensuboxyds." Ber. dtsch. chem. Ges., 39:1915.

Über das Vertheilungsprincip. Ber. dtsch. chem. Ges., 39:2138.

Über den Verlauf der addition von Wasser an Hexin-2. Ber. dtsch. chem. Ges., 39:2143.

With R. N. Hartman. Zur Constitution des aus Mannit-Hexen dargestellten Hexylalkohols. Ber. dtsch. chem. Ges., 39:2149.

Über die Einwirkung von Chlor auf Hexan. Ber. dtsch. chem. Ges., 39:2153.

With V. L. Leighton. Über die Addition von Unterchloriger säure an Isobuten. Ber. dtsch. chem. Ges., 39:2157.

With F. D. Wilson. Über den Verlauf der Zersetzung von gemischten Fettäthern durch Jodwasserstoffsaure. Ber. dtsch. chem. Ges., 39:2569.

Über die Einwirkung von Salzsäure auf Propenoxyd und Propenalkohol. Ber. dtsch. chem. Ges., 39:2785.

With V. L. Leighton. Über die Einwirkung von Salzsäure auf Isobutenoxyd. Ber. dtsch. chem. Ges., 39:2789.

With A. B. Lamb. The isomerism of ethyl coumaric and ethyl coumarinic acids. Am. Chem. J., 36:552.

1907

With R. N. Hartman. Zur Konstitution des aus Mannit dargestellten Hexyljodids. Ber. dtsch. chem. Ges., 40:140.

With H. Hibbert. On the ammonia reaction as a means of distinguishing between enol and keto derivatives. I. Ber. dtsch. chem. Ges., 40:4380.

With H. Hibbert. The ammonia reaction as a means of distinguishing between enol and keto derivatives. II. Ber. dtsch. chem. Ges., 40:4916.

Die van't Hoff-Wislicenusache Konfigurationslehre. J. prakt. Chem., 75:105.

1908

Stereoisomerism and the law of entropy. Am. Chem. J., 39:1.

With H. D. Smith. The addition of halogens to cinnamic acid and some of its derivatives. Am. Chem. J., 39:16.

Über Desmotropie und Merotropie. I. Ann. Chem., 363:20.

With H. D. Smith. II. Die tertiären Amine als Reagentien zur Unterscheidung zwischen stabilen Enol- und Ketonderivaten. Ann. Chem., 363:36.

With P. H. Cobb. III. Phenylisocyanat als Reagens zur Festellung der Constitution Merotropen Vergindungen. Ann. Chem., 363:64.

With A. Murphy, Jr. IV. Acetylchlorid und Essigsäureanhydrid als Reagentien zur Unterscheidung zwischen Enol- und Ketonderivaten. Ann. Chem., 363:94.

With W. W. Garner. Magnesium permanganate as an oxidizing agent. Monatshefte fuer Chemie und Verwandte Teile Anderer Wissenschaften, 22:556.

With J. E. Bucher. Zur Frage über die Festellung der Konstitution der Phenylnaphthalindicarbonsäure; Hrn. Hans Stobbe zur Antwort. Ber. dtsch. chem. Ges., 41:70.

Über refraktometrischen Beweis der Konstitution des "Kohlensuboxyds." Ber. dtsch. chem. Ges., 41:925.

With H. Hibbert. Über die vermeintliche Beziehung zwischen Dielektrizitätskonstante und isomerisierender Kraft organischer Losungsmittel bei Enol-Keton-Desmotropen. Ber. dtsch. chem. Ges., 41:1080.

With O. D. E. Bunge. Über den stereochemischen verlauf der Addition von Chlor zu Crotonsäure. Ber. dtsch. chem. Ges., 41:2907.

1909

With H. Hibbert. V. Zur Constitution des Cyanwasserstoffs. Ann. Chem., 364:64.

With H. Hibbert. VI. Zur Constitution der Cyansäure. Ann. Chem., 364:129.

With R. F. Brunel. On the relative ease of addition in the alkene group. First paper on the laws of addition in organic chemistry. Am. Chem. J., 41:118.

Zur theorie der Esterfikation organischer Carbonsäuren. (Erste Mitteilung über die Natur der "sterischen Hinderung"). Ber. dtsch. chem. Ges., 42:310.

With K. J. Oechslin. Über den Einfluss der substituenten aromatischer Carbonsäuren auf ihre Esterifikation. II. Ber. dtsch. chem. Ges., 42:317.

Das chinon von Standpukt des Entropiegesetzes und der Partialvalenzhypothese. J. prakt. Chem., 79:418.

With K. Wolgast. Über die Beziehung zwischen Struktur des Fettalkohole und Geschwindigkeit der Esterifikation. III. Ber. dtsch. chem. Ges., 42:3157.

With K. Wolgast. Zur Darstellung reiner Ketone mittels Acetessigester. Ber. dtsch. chem. Ges., 42:3176.

1910

Über die Beziehung zwischen Structure der Fettalkohole und geschwindigkeit der Esterifikation. Ber. dtsch. chem. Ges., 43:464.

Über die "Additionstheorie," Hrn. S. J. Acree zur antwort. Ber. dtsch. chem. Ges., 43:621.

On the application of physical chemical methods to determine the mechanism of organic reactions. Am. Chem. J., 43:322.

Outline of a theory of organic chemistry founded on the law of entropy. J. Am. Chem. Soc., 32:990.

With A. Murphy, Jr. On the action of chlorine in solution in carbon tetrachloride and of carbon tetrachloride on metallic oxides. Am. Chem. J., 44:365.

With P. H. Cobb. Über die Reaktion zwischen Chinon und Salzsäure. J. prakt. Chem., 82:297.

Über den Mechanismus der Chinonreaktionen. Hrn. Theodor Posner zur erwiderung. J. prakt. Chem., 82:306.

1911

With H. Leupold. Zum verlauf der intramolekularen Umlagerungen bei den Alkylbromiden und zur Frage der Ursache des Gieichgewichtszustandes bei Unkehrbaren reaktionen. Ann. Chem., 379:263.

1912

With R. F. Brunel. Action of aqueous solutions of acids on alkenes. Am. Chem. J., 48:267.

With F. Zeidler. Chemistry of the amyl series. Ann. Chem., 385:227.

Number of isomers in merotropic and desmotropic compounds. I. Ann. Chem., 390:30.

Number of isomers in merotropic and desmotropic compounds. II. Isomeric keto forms of acetyldibenzoylmethane. Ann. Chem., 390:46.

With Harold Hibbert. Number of isomers in merotropic and desmotropic compounds. III. Isomeric keto forms of propionyldibenzoylmethane. Ann. Chem., 390:68.

Number of isomers in merotropic and desmotropic compounds. IV. Isomeric forms of formylphenylacetic ester. Ann. Chem., 391:235.

With G. P. Fuller. Number of isomers in merotropic and desmotropic compounds. Isomeric enol forms of formylphenylacetic ester. Ann. Chem., 391:275.

With F. Zeidler. Course of intramolecular rearrangements in alkyl bromides. Ann. Chem., 393:81.

Application of the "scale of combined influence" to explain the ionization constants of organic acids, and a reply to C. G. Derik. J. Am. Chem. Soc., 34:849.

1913

The Perkin reaction. Am. Chem. J., 50:411.

With E. Scharf. Über den Mechanisms der Einwirkung von Brom auf Fettsaurechloride. Ber. dtsch. chem. Ges., 46:135.

1914

With W. Schlenk, J. Appenrodt and A. Thal. Über Metalladitionen en mehrfache Bindungen. Ber. dtsch. chem. Ges., 47:473.

Number of isomers of merotropic and desmotropic compounds. VI. Isomeric forms of formylphenylacetic ester. Ann. Chem., 406:137.

1916

With E. Scharf and K. Voigt. Rearrangement of iso into tertiary butyl bromide. J. Am. Chem. Soc., 38:653.

1918

Configurations of organic compounds and their relation to chemical and physical properties. J. Am. Chem. Soc., 40:704.

Configurations of organic compounds and their relation to chemical and physical properties. II. The relations between the physical properties and the configurations of unsaturated acids. J. Am. Chem. Soc., 40:1674.

1919

Relations between the chemical structures of carbonyl derivatives and their reactivities towards salts of semicarbazide. J. Am. Chem. Soc., 41:393.

1920

The chemical mechanism of organic rearrangements. J. Am. Chem. Soc., 42:787.

The non-existence of valence and electronic isomerism in hydroxylammonium derivatives. J. Am. Chem. Soc., 42:1232.

1921

The structures and reactions of hydroxylamine and its derivatives. I. J. Am. Chem. Soc., 43:315.

1929

Castor-oil preparation. Australian patent 20,127.

1930

With J. Ross. Course of addition of sodium enol alkyl malonic esters to α,β-unsaturated esters. J. Am. Chem. Soc., 52:4598.

1931

With J. Ross. Course of addition of sodium enol alkylmalonic and sodium enol alkylcyanoacetic esters to unsaturated esters. J. Am. Chem. Soc., 53:1150.

With J. Ross. $\alpha\beta\gamma$-Trimethylglutaric acids. J. Am. Chem. Soc., 53:1175.

With J. Ross. Partition principles as applied to the structures of enolic sodium derivatives of 1,3-diketones and β-keto esters. J. Am. Chem. Soc., 53:2394.

1932

With J. Ross. Partition principles as applied to the structure of enolic sodium derivatives of 1,3-diketones and β-keto esters. II. J. Am. Chem. Soc., 54:387.

With J. Ross. Addition of sodium enol alkylmalonic ester to benzalacetophenone. J. Am. Chem. Soc., 54:407.

1933

With J. Ross. Course of addition of the sodium enolates of malonic and methylmalonic esters to benzalacetophenone and to crotonic ester. J. Am. Chem. Soc., 55:1632.

With J. Ross. Carbon syntheses with malonic and related acids. I. J. Am. Chem. Soc., 55:3684.

1934

With N. Weiner. Formation of enolates from α-lactonic esters. J. Am. Chem. Soc., 56:2012.

1935

With G. H. Carlson. Mechanism of reactions of acetoacetic ester, the enolates and structurally related compounds. I. C- and O-Alkylation. J. Am. Chem. Soc., 57:159.

The mechanism of the reactions of metal enol acetoacetic ester and related compounds. II. Sodium enolates toward acyl chloride. J. Am. Chem. Soc., 57:165.

With G. H. Carlson. Mechanism of the nitration process. J. Am. Chem. Soc., 57:1268.

1936

With N. Weiner. Mechanism of the sulfonation process. J. Am. Chem. Soc., 58:294.

Mechanism of the reactions of metal enol acetoacetate ester and related compounds. III. Copper enolates. J. Am. Chem. Soc., 58:353.

With N. Weiner. Carbon syntheses with malonic acid and related compounds. II. Aromatic aldehydes. J. Am. Chem. Soc., 58:680.

With N. Weiner. Formation of enolates from lactonic esters. J. Am. Chem. Soc., 58:999.

1937

With N. Weiner. 1,2- and 1,4-Addition. I. The 1,4-addition of potassium isocyanate. J. Am. Chem. Soc., 59:744.

With G. H. Carlson. 1,2- and 1,4-Addition. II. Nitrogen tetroxide and trimethylethylene. J. Am. Chem. Soc., 59:843.

Course of the addition of malonic enolates to α,β-unsaturated esters. J. Org. Chem., 2:303.

1938

With N. Weiner. The partition principle as applied to the structures of enolic sodium derivatives of β-diketones and β-keto esters. III. J. Org. Chem., 3:372.

1939

With G. H. Shadinger. Influence of solvents on the stereochemical course of the addition of hydrogen bromide to monobasic acetylenic acids and the relation of solvent effect to chemical structure. J. Org. Chem., 4:128.

With G. H. Carlson. 1,2- and 1,4-Addition. III. Nitrogen trioxide and trimethylethylene. J. Org. Chem., 4:169.

The relations of "oxygen and peroxide effect," and of hypochlorous acid addition, to the structures of unsaturated organic compounds. J. Org. Chem., 4:519.

With N. Weiner. Solvent and peroxide effect in the addition of hydrogen bromide to trimethylethylene. J. Org. Chem., 4:531.

1940

With G. H. Carlson. 1,2- and 1,4-Addition. IV. Nitrogen tetroxide and isobutylene. J. Org. Chem., 5:1.

With G. H. Carlson. 1,2- and 1,4-Addition. V. Nitrogen tetroxide and tetramethylethylene. J. Org. Chem., 5:14.

With N. Weiner. Solvent and peroxide effect in the addition of hydrogen bromide to unsaturated compounds. IV. Isopropylethylene. J. Org. Chem., 5:389.

1943

With C. M. Saffer, Jr. The addition of triphenylmethylsodium and phenyllithium to cinnamic ester and benzalacetophenone. J. Org. Chem., 8:60.

With H. S. Mason. Normal addition of hydrogen bromide to 3-butenoic, 4-pentenoic and 5-hexenoic acids in hexane. J. Am. Chem. Soc., 65:683.

With H. S. Mason. Determination of the composition of mixtures of α-bromo-α-methyl, and α-bromo-β-methylsuccinic acids. J. Org. Chem., 9:393.