FROM COSMOCHEMISTRY TO FUEL CELLS: NOTES ON EMIL BAUR, PHYSICAL CHEMIST

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Introduction

Few historians of chemistry will be familiar with the name Emil Baur (1873-1944), except perhaps if they specialize in the history of fuel cells. Although he has an entry in Poggendorff's *Handwörterbuch*, he is not described in either *Lexikon bedeutender Chemiker* or *Dictionary of Scientific Biography* (1). Yet Baur, a second-generation physical chemist, was far from an obscure scientist in his own time, and during his long and distinguished career in Zurich he contributed interesting work covering a wide range of the chemical landscape. From 1911 to 1942 he was professor at the Polytechnic University better known as the ETH (Eidgenössische Technische Hochschule). The only biographical accounts of Baur are two obituaries written by William Dupré Treadwell, who from 1916 to 1918 worked under Baur at the ETH Institute of Physical Chemistry and subsequently served as professor of analytical chemistry at the ETH (2).

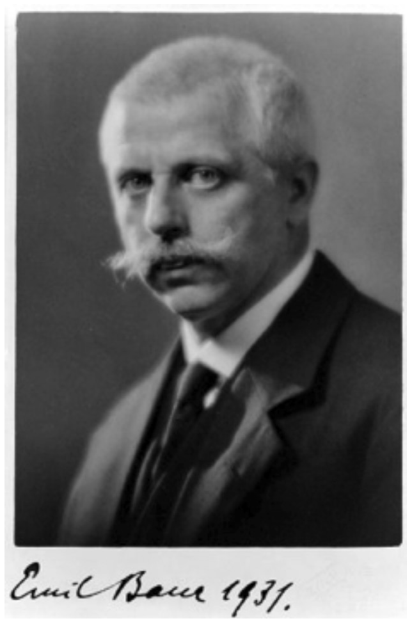

Figure 1. Emil Baur. Source: ETH Library, Zurich, picture archive.

Apart from providing some biographical information concerning Baur, this paper discusses select cases of his scientific work, including rare earth research, mineralogy, chemical kinetics, and his extensive electrochemical research on fuel cells. In addition, it describes his brief connection to Einstein and also Baur's views on the more general aspects of physical chemistry, including his possible anti-atomism (3).

Emil Baur, Life and Work

The German-Swiss physical chemist and electrochemist Emil Baur was born in Ulm in Württemberg, southern Germany, on 4 August 1873, the son of Adolf Baur, a merchant and civil servant, and Agnes Baur, née Adam. He was thus a fellow-townsman to the six years younger Albert Einstein. In 1905 Adolf Emil Baur (to use his full name) married Ottilia Mayer with whom he had two children, Alice born in 1908 and Arthur in 1915. The latter became a well-known author and linguist (4).

After having completed his high school (Gymnasium) education in Ulm and Baden-Baden, Emil Baur studied chemistry in Berlin and Munich. For a brief period of time he worked as an apprentice at the Arabol Manufacturing Company in New York, a firm specializing in the production of gums, glues, and textile chemicals. He wrote his first research papers in 1897. Baur subsequently became an assistant to Friedrich Wilhelm Muthmann, professor of inorganic chemistry at the Munich Technical University. While in Munich, Baur gave a public lecture course on "chemical cosmography" to be considered below.

In 1901 Baur wrote his professorial thesis (*Habilitation*), which granted him the right to lecture at German universities as a *Privatdozent*. The subject of the thesis was an investigation of a nitrogen-hydrogen fuel cell with liquid ammonia as electrolyte. In this connection Baur also investigated the ammonia synthesis process

$$N_2 + 3\,H_2 \rightarrow 2\,NH_3 + 92\text{ kJ mol}^{-1}.$$

At the time this reaction attracted intense interest, which eventually resulted in the momentous Haber-Bosch industrial process. Apart from measuring the voltage of the cell as 0.6 V, he reported experiments on ammonia synthesis with catalysts such as platinum powder and chromium nitride, suggesting that small amounts of NH_3 might have been formed (5). Although his work did not lead to a breakthrough, it was recognized as an important part of the preparatory phase of the history of synthetic ammonia production (6).

In the winter semester 1904-1905 Baur served as assistant to Wilhelm Ostwald at his Institute of Physical Chemistry in Leipzig, and from there he went to Berlin to work as scientific assistant at the Imperial Health Bureau (Kaiserliche Gesundheitsamt), an institution founded in 1876. Two years later he accepted an offer as extraordinary professor of physical chemistry and electrochemistry at the Braunschweig Technical University. During his period in Braunschweig he published in 1907 an introductory book on spectroscopy and colorimetry, and in 1910 a book on themes of physical chemistry based on lectures given to the German Association of Engineers (7). Svante Arrhenius recommended the latter book for its excellent lecture demonstrations (8).

In October 1911 Baur was appointed full professor in physical chemistry and electrochemistry at the ETH, one of Europe's most prestigious institutions of chemistry and physics. Although founded in 1855, ETH had only recently acquired full university status, the first doctorates being awarded in 1909. The federal ETH should not be confounded with the University of Zurich, which was established in 1833 as a cantonal school. Since 1897 the Austrian chemist Richard Lorenz had served as professor of electrochemistry at ETH, but in 1910 Lorenz left Zurich to take up a position at the Frankfurt Academy, which a few years later became the University of Frankfurt am Main. Baur not only succeeded Lorenz but also the German chemist Georg Bredig, who had come to Zurich in 1910 as professor of physical chemistry. However, Bredig only stayed one year after which he moved on to a chair at the Technical University of Karlsruhe (9). Baur, on the other hand, stayed in Zurich until the end of his life.

During his career as professor of ETH, Baur did research in a broad range of the chemical sciences. Although most of his papers were in photochemistry, electrochemistry, and organic chemistry, he also did much work in what today would be classified as materials science. The author or coauthor of three books and more than 160 articles, all of them in German, he was a productive scientist (10). Of the 148 papers listed in *Web of Science*, 90 had Baur as sole author and 58 were written with one or more coauthors. Most of the papers appeared in *Zeitschrift für anorganische Chemie*, *Zeitschrift für physikalische Chemie*, *Zeitschrift für Elektrochemie*, or *Helvetica Chimica Acta*.

Baur retired from his position at ETH in 1942 and passed away on 14 March 1944. During his brief period of retirement he focused on studies of natural philosophy. Following Baur's retirement the ETH chair in physical chemistry was occupied by Gottfried Trümpler, a former collaborator of and assistant to Baur.

Baur and Einstein

Not only was Baur born in the same town as Einstein, he also came to know the famous physicist during Einstein's brief stay as a professor at ETH from the summer of 1912 to the spring of 1914 (when Einstein left for Berlin). ETH was not new to Einstein, for this was the school where he had studied 1896-1900 and from which he received his diploma in physics. In his younger days he was seriously interested in problems of physical chemistry, including such topics as photochemistry, statistical mechanics, chemical thermodynamics, and the quantum theory of gases. Indeed, it has been claimed that "young Einstein was at heart a chemist" (11). Einstein's very first paper, an investigation of capillarity dating from 1901, was squarely in the tradition of physical chemistry, relying to a large extent on data from Ostwald's *Lehrbuch der allgemeinen Chemie* (12).

The Russian-born chemist David Reichinstein taught electrochemistry at the University of Zurich from 1911 to 1918 and was acquainted with both Einstein and Baur. After World War I he returned for a while to Russia, having just become the Soviet Union, where he became professor of physical chemistry at the University of Nizhny Novgorod (13). In a biography of Einstein published in 1934, Reichinstein told how Baur came to meet the father of relativity theory: "My friend, Professor Baur, wanted to make Einstein's acquaintance. I mentioned this to Einstein and gave a description of the good qualities of my friend. … We went to a small café where Baur was expecting us" (14). According to Reichinstein, Einstein made a deep impression on Baur:

> He [Baur] was overwhelmed by Einstein's quality of emotion, by something direct which radiated from him, by his spirituality, but particularly by the ease with which Einstein produced the most intricate problems "out of his hat" so to speak. "How can he possess so much knowledge of scientific literature at this early age?"

While in Zurich, Einstein organized a series of weekly colloquia. In one of them Max von Laue presented his new theory of X-ray diffraction in crystals, the implications of which Einstein discussed. On leaving the colloquium, Reichinstein recalled (15):

> I walked beside Professor Baur and he repeated what he had said at the time of making Einstein's acquaintance at the café: "Einstein extemporizes on the most intricate problems with as much ease as if he were talking about the weather. Others need a lot of time and have to work hard to merely understand and digest every one of these problems he was talking about."

In yet another Zurich colloquium, probably on 23 July 1913, Einstein lectured on a theory of surface fluctuations recently published by the Russian physicist Leonid Mandelstam, who at the time worked in Strasbourg. After the lecture Einstein sent Mandelstam a postcard signed by, among others, Baur, Reichinstein, von Laue, and Otto Stern (16). Whereas Baur co-signed Einstein's postcard to Mandelstam, on 19 November the previous year Einstein co-signed a letter which Baur wrote to August Horstmann, the pioneer of physical chemistry and chemical thermodynamics, on the occasion of his seventieth birthday (17). Also Reichinstein and Alfred Werner, who since 1895 had been professor of chemistry at the University of Zurich, signed the letter of congratulation.

Stern, who would later receive the physics Nobel Prize for his development of the molecular beam method, had obtained his doctorate in Breslau under the physical chemist Otto Sackur. The subject of the doctoral thesis was the osmotic pressure of CO_2 in highly diluted solutions. He subsequently joined Einstein as his first assistant in Prague, and when Einstein moved to Zurich he brought young Stern with him.

Stern's *Habilitation* thesis, an 8-page essay on the kinetic theory of the vapor pressure of monoatomic solids, was evaluated by a committee consisting of Einstein, Baur, and the French ETH physicist Pierre-Ernest Weiss. While Einstein was enthusiastic, Baur was more reserved, but in the summer of 1913 the committee accepted the thesis with the result that Stern became a *Privatdozent* and could continue his collaboration with Einstein on the quantum theory of diatomic molecules. At the end of his evaluation, Baur wrote (18):

> In the eighties of the last century physical chemistry experienced a stormy development through the theory of osmotic pressure, the free ions and the phase rule. However, in the nineties a certain degree of stagnation set in. Since the previous decade, however, one observes a new growth which ultimately is based on Planck's radiation theory. It would be most desirable to have a lecture on the chemical applications of this new research area, and it seems to me that Mr. Stern has all the qualifications that are necessary for honoring this task.

Although Baur thus recognized the importance of quantum theory for physical chemistry, he did not himself contribute to this early phase of quantum chemistry. When the old Planck-Bohr quantum theory was replaced by the new quantum mechanics and in 1927 led to the Heitler-London theory of the covalent bond (work done in Zurich), Baur showed no interest. His concern was with classical physical chemistry and not with quantum chemistry or what soon emerged as chemical physics.

Philosophy of Nature

According to his biographer and collaborator William Treadwell, Baur had an "unusually broad knowledge of natural philosophy and humanist culture" (19). He may have had this interest since his youth, as indicated by a correspondence he had with the famous Viennese philosopher-physicist Ernst Mach. Baur was at the time interested in the question of whether or not life could be explained purely in chemical terms, a subject on which Mach offered his opinion. "I do not believe that the chemical laws known to us presently are sufficient to explain organic life," Mach told his young correspondent (20). On the other hand, Mach did not rule out that such an explanation would appear in the future.

Another indication of Baur's humanist interests is provided by an insightful review he wrote of a book dealing with the relationships between science and the arts. The book was written by Felix Auerbach, a German physicist, humanist and promoter of the arts (21). In 1935 Baur published anonymously a complex and learned literary-philosophical novel, *Das Helldunkel*, in which he discussed at length his pantheistically colored view of culture, religion and nature (22). Although the book had little to say about physics and chemistry, he briefly expressed his dissatisfaction with the world view of modern physics.

There is little doubt that Baur's general view of science was strongly influenced by the ideas of Mach and Ostwald, which he much appreciated and often quoted. Neither Mach nor Ostwald before 1908 believed in the existence of atoms as physically real particles, and it is possible that Baur belonged to the dwindling minority of physical chemists sharing their view. In an interview of 1962 conducted by Thomas Kuhn, Stern recalled that when he was a *Privatdozent* in Zurich, "the professor of physical chemistry said to him that he could never have passed any of the physical chemistry exams at Zurich because he was a believer in atoms" (23). In an earlier interview of 1961, he mentioned specifically Baur as an opponent of molecular and atomic theory (24). Although Baur never explicitly denied the existence of atoms, it is remarkable that in his many works he very rarely referred to or made use of terms such as atoms or ions. In agreement with Ostwald he wanted to base chemistry on the laws of stoichiometry that do not presuppose an atomic constitution of matter (25).

In addition to stoichiometry Baur was keenly interested in reaction kinetics, a field he contributed to with several studies during the last phase of his career. Baur was fascinated by the so-called "Wegscheider's paradox," which refers to the Austrian chemist Rudolf Wegscheider, who in 1901 pointed out that the condition of vanishing reaction rate as given by chemical kinetics does not necessarily coincide with the thermodynamic equilibrium condition (26). He vaguely suggested that thermodynamics might not be applicable to all reversible chemical processes. Baur felt that a change in philosophical outlook was required if the thermodynamic concept of chemical equilibrium was to be reconciled with the one based on kinetic theory. The price to pay would be "a revision of Democritus' materialistic natural philosophy to which modern physical theory remains faithful to this day" (27). As an alternative to atomistic materialism he advocated a return to a "hylozoic" natural philosophy, the view that all matter is in some sense alive and composed of a unity of forces that extends from the simplest molecules to living beings. Baur thought that hylozoism might be the only way to bridge chemistry not only with physics but also with biology.

According to Baur, the chemical equilibrium state might in some cases not be an ordinary dynamical equilibrium governed by the principle of detailed balance, but what he called a one-way circular reaction or circular equilibrium. Wegscheider's paradox and equilibria of the cyclical kind had earlier been discussed by the eminent American chemist Gilbert Lewis, according to whom cyclical equilibria did not exist (28). Baur's interest in circular or cyclical reactions has led Boris Yavelov to suggest that the Belousov-Zhabotinsky oscillating reaction has its origin in Baur's laboratory in Zurich. Boris Belousov graduated from ETH in 1915 and according to Yavelov, "Belousov's idea of periodical chemical reactions was prompted by Baur's works" (29). However, Baur's interest in cyclic reactions dated from the 1930s and Belousov only studied the kind of oscillating reactions named after him in about 1950 (30). For these reasons a connection is highly unlikely.

In any case, Baur thought that cases of one-way circular reactions might be realized in biochemical life processes and that they possibly violated the second law of thermodynamics (31). In his last paper, a lengthy review of chemical kinetics published shortly after his death in March 1944, he stated that his discovery of one-way circular reactions "necessitates a re-evaluation of chemical kinetics of such a range that it affects the domain of validity of the second law of thermodynamics" (32). Baur extended the apparent violation of chemical entropy increase to a cosmological scale, arguing that one-way circular reactions provided a way to prevent the so-called "heat death" of the universe caused by the continual and irreversible increase in entropy. In agreement with an older idea of Walther Nernst, who was strongly opposed to the heat death, Baur tended to conceive the universe as an eternal one-way circular process on the largest possible scale (33). Baur's somewhat unorthodox ideas of reaction kinetics did not attract much interest, but in the early 1950s they were taken up and further developed by Anton Skrabal, an Austrian chemist (34).

Rare Earths

Despite his lack of interest in quantum and atomic theories, Baur was a versatile chemist with an unusually broad interest in chemistry and its allied sciences. Together with Muthmann, his professor in Munich, he examined in 1900 the phosphorescence spectra of lanthanum and yttrium earths. This line of research was followed up by another collaborative work, this time with his colleague at Munich, Robert Marc, which dealt with the much-discussed problem of the number of rare earth elements (35).

One of the methods of determining whether an earth metal was elementary or consisted of more elements was at the time to study the luminescence spectra of rare earths exposed to cathode rays. By means of this technique, sometimes called "phosphorescent spectroscopy," the British chemist William Crookes had suggested in 1888 that yttrium contained several "meta-elements" of different atomic compositions yet belonging to the same element (36). Crookes' claim was controversial and contested by the Frenchman Paul-Emile Lecoq de Boisbaudran, among others, who held that yttrium was not elementary but consisted of two new elements (which he designated Z_α and Z_β). Still in 1900 there was a great deal of confusion with regard to the number of rare earth elements and their place in the periodic system (37). Baur and Marc showed that pure yttrium, gadolinium, and lanthanum did not produce discontinuous luminescence spectra, and that the observations of Crookes and Boisbaudran could be explained as due to traces of the elements erbium, neodymium, and praseodymium. While ignoring Crookes' meta-elements, they concluded that Boisbaudran's suggestion of new elements was unfounded (38). Baur's early research on the rare earths was not particularly important, but it was well known among specialists in the field (39).

A decade later Baur returned to the question of the rare earths, this time in a discussion of the periodic system. This was a little before X-ray spectroscopy and radiochemistry revealed the existence of the atomic number, and at a time when chemists still believed that the atomic weight was the ordering principle of the periodic system. Consequently there was a great deal of confusion with respect to the details of the system. Baur based his analysis of the periodic system on the curve of atomic volumes originally demonstrated by Lothar Meyer in 1870, but instead of plotting atomic volumes against atomic weights Baur used the logarithms of the volumes (40). In this way he found that the rare earth metals formed a zig-zag line commencing at lanthanum below barium and ending with lutetium above tantalum (Figure 2). Baur concluded that there were twelve rare earth elements. Lanthanum belonged to group III, series 8, and cerium to group IV, series 8, and the remaining elements were placed in their own group between lanthanum and cerium (Figure 3). According to Baur, it followed from his system that there could be no more elements than those already known. In this he was quite wrong, of course. Only with advances in X-ray spectroscopy and

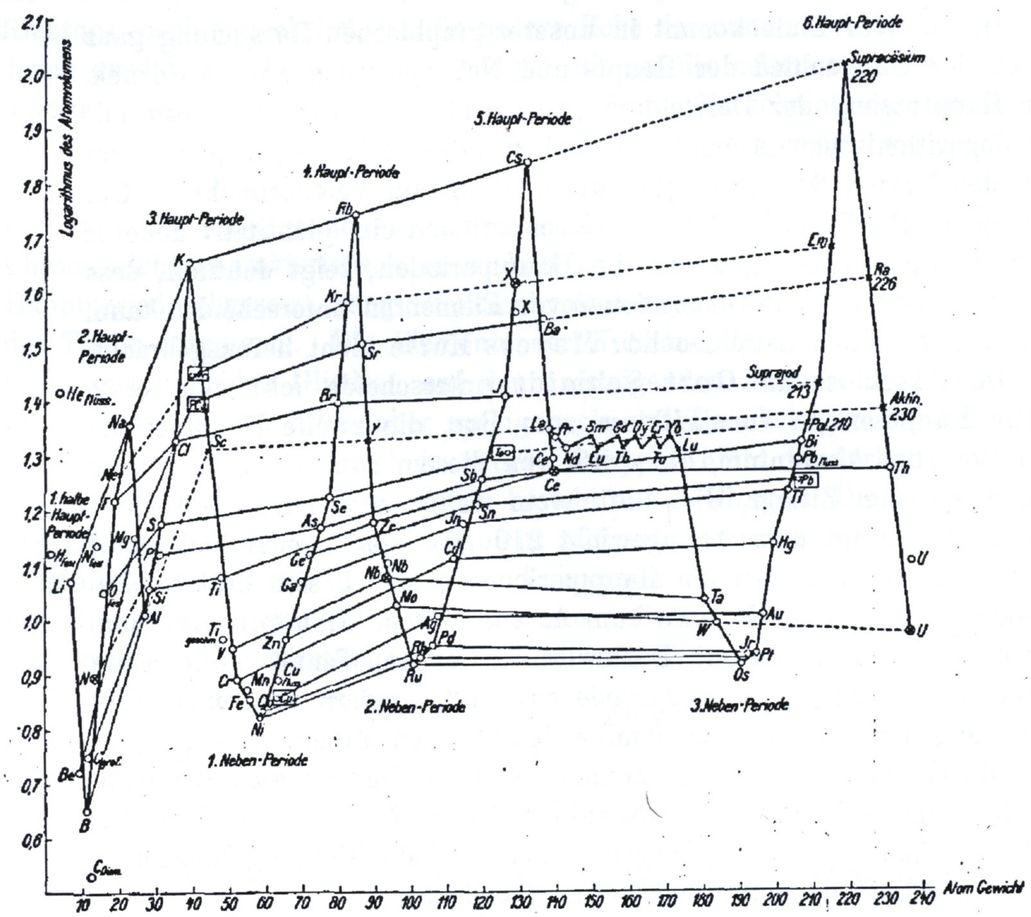

Figure 2. *Baur's semilogarithmic depiction of atomic volumes. Source: Ref. 40 (Baur), p 572.*

atomic theory was the tricky question of the position of the rare earths in the periodic system eventually resolved.

Das periodische System der Elemente.

Die Klammern bedeuten Anfang und Ende der Hauptperioden.

Nullte Gruppe	Erste Haupt-, Neben-gruppe	Zweite Haupt-, Neben-gruppe	Dritte Haupt-, Neben-gruppe	Vierte Haupt-, Neben-gruppe	Gruppe der seltenen Erden	Fünfte Haupt-, Neben-gruppe	Sechste Haupt-, Neben-gruppe	Siebente Gruppe	Eisen-Platin-gruppe
He	*Li*	*Be*	*B*]	[*C*		*N*	*O*	*F*	
Ne	*Na*	*Mg*	*Al*]	[*Si*		*P*	*S*	*Cl*	
Ar	*K*	*Ca*	*Sc*	*Ti*]		*V*	*Cr*		*Mn Ni* *Fe Co*
Kr	*Cu* *Rb*	*Zn* *Sr*	*Ga* *Y*	*Ge* *Zr*]		[*As* *Nb*	*Se* *Mo*	*Br*	*Ru Rh Pd*
X	*Ag* *Cs*	*Cd* *Ba*	*In* *La*	*Sn* *Ce*]	*Pr Sm Gd Dy Er Yb* *Nd Eu Tb Ho Tu Lu*	[*Sb* *Ta*	*Te* *W*	*J*	*Os Ir Pt*
Em	*Au* Supra-cäs.	*Hg* *Ra*	*Tl* Akt.	*Pb* *Th*		[*Bi* Supra-tantal	Pol. *U*	Supra-jod	

Figure 3. *Baur's proposal of the periodic system. Source: Ref. 40 (Baur), p 583.*

Mineralogical and Oceanographic Chemistry

As a young man Baur was seriously interested in mineralogy, geology, and geochemistry, subjects that appeared prominently in his book on chemical cosmography and on which he wrote a few scientific papers. He was a contributor to the 1915 edition of *Handbuch der Mineralchemie*. There was in the early part of the twentieth century a growing interest in applying physical chemistry to geology and mineralogy, and Baur contributed to the trend (41). In a paper of 1903 he investigated the conditions under which quartz would be formed from heating of amorphous silica (SiO_2) with potassium aluminate ($K_2Al_2O_4$) at high temperature and pressure (42). Baur illustrated his results with diagrams based on the phase rule of Gibbs and van 't Hoff, which possibly was the first mineralogical use of the rule. In the third edition of his monograph on the phase rule, the British physical chemist Alexander Findlay called attention to Baur's paper as an indication that the study of the phase rule as applied to mineral formation, although still in its infancy, gives "promise of a rich harvest in the future" (43).

It was only with the so-called "mineralogical phase rule" formulated by the Norwegian geologist and geochemist Victor Moritz Goldschmidt in 1911 that the phase rule appeared as a powerful tool in petrology (44). According to this rule the number of phases in a rock, corresponding to the number of minerals, will not exceed the number of chemical components. In a lecture to the German Bunsen Society for Applied Physical Chemistry of 1911, Goldschmidt demonstrated how the rule can be used to gain information about temperatures and pressures of silicate rock formation (45). Baur, at the time still at the Braunschweig Technical University, attended the lecture and objected to some of Goldschmidt's conclusions, which he thought lacked justification in terms of physical chemistry. On this occasion Baur did not refer to his own work of 1903 and he did not engage in public polemics with Goldschmidt. On the other hand, he got indirectly involved into a controversy between Goldschmidt and Johann Koenigsberger, a mineralogist and mathematical physicist at Freiburg University. Part of this controversy concerned the priority of the phase rule applied to minerals, which according to Koenigsberger belonged to Baur. In reply to Koenigsberger, Goldschmidt denied that this was the case: "Mr. E. Baur gives indeed an excellent description of a particular system, but he has nothing to say about the general relationship between the number of phases and the number of minerals in a naturally stable system" (46).

During the first half of the twentieth century several chemists and oceanographers tried to determine the amount of gold in seawater and, if possible, to recover the precious metal. Baur was one of them. In 1913 he was granted a British patent (BP 16898) on means of obtaining noble metals from highly diluted solutions, and in 1916 it was followed by a German patent (DRP 272654). The patents failed to attract commercial interest. At about the same time he supervised Hellmuth Koch, a graduate student who on his instigation wrote a doctoral thesis on a method to determine small amounts of gold by means of adsorption on charcoal (47). After Germany's devastating defeat in World War I, Fritz Haber and his Kaiser Wilhelm Institute of Physical Chemistry in Berlin engaged in an ambitious scheme of separating gold from seawater on an industrial scale. However, in 1927 he was forced to admit that the average concentration of gold in the oceans was too low to allow economic recovery (48).

Baur followed Haber's work closely and in 1942 he wrote two systematic reviews of the subject which

Table 1. Contents of Baur's *Chemische Kosmographie* (1903).

Chapter	**Content**
1	Kirchhoff's radiation laws; spectral analysis; composition of the Sun
2	Blackbody radiation; Sun's temperature; the photosphere
3	Stellar spectra; comets and nebulae; decomposition of chemical elements
4	Composition of meteorites; the stone from Ovifak; the world fire
5	Limits between gaseous-liquid and liquid-solid phases; petrographic and chemical composition of stones
6	Solidification of magma; volcanic eruptions; pneumatic mineral formation; contact metamorphosis; circuit of substances in the mineral kingdom
7	Artificial manufacture of minerals
8	Composition of the oceans; formation of oceanic salt deposits
9	Formation of oil and coal; cellulose's methane fermentation; formation of saltpeter
10	Proteins; architecture of protein molecules
11	Fermentations; structure of carbohydrates
12	Reversion of fermentative action; photosynthesis of carbohydrates; synthesis of amino acids; presence of life
13	Metabolism in animals; proteins in animal tissue; combustion of carbohydrates; fats; the source of muscular power
14	Properties and chemistry of living substances; the ideas of E. Hering and E. Mach

included proposals of new techniques to recover the gold (49). According to the results obtained by Baur and his collaborators in Zurich, Haber's values for the concentration of gold—on the average 0.01 mg m^{-3}—were too low. It was, they thought, too early to rule out a production of gold based on seawater. While Baur did not engage in oceanographic determinations of the content of gold, his doctoral student Walter Stark did (50). Using the measurement methods of Baur and Koch, Stark found that in some European locations the content of gold in seawater was as high as 2 mg m^{-3}.

Chemical Cosmography

In the winter semester 1902-1903 Baur gave a series of public lectures at the Munich Technical University on what he called "chemical cosmography"—probably a term he coined for the occasion (51). By this term he meant the chemical processes in all of nature, which he divided into three groups: the chemistry of the stars, chemical transformations in the crust of the Earth, and chemical aspects of organic nature. The book was organized in 14 chapters, each corresponding to a lecture in the Munich lecture series (see Table 1). In the first lecture, dealing with the chemistry of the Sun, Baur subscribed to the hypothesis of the non-terrestrial element "coronium." In agreement with several other chemists and astronomers at the time, he assumed coronium to be lighter than hydrogen. Only in 1939 were the spectral lines of coronium identified as due to the ion Fe^{13+}.

Baur's wide-ranging and synthetic survey of chemistry, aiming to connect the chemist's laboratory with the heavens as studied by the astronomer, was in the tradition of what at the time was known as "cosmical physics" (52). The difference was that its approach was chemical rather than physical. Baur's collection of subjects included many of those dealt with by the cosmical

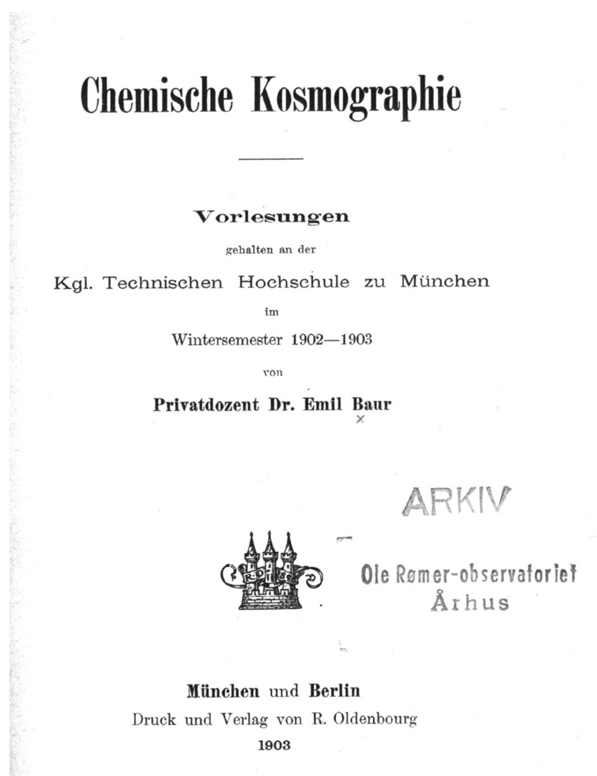

Figure 4. *Baur's* Chemical Cosmography *of 1903.*

physicists, such as the constitution of the Sun, meteorites, comets, volcanoes, and the composition of sea water. On the other hand, it was even broader by covering also aspects of organic nature, including biochemistry, photosynthesis, fermentation processes, and the nature of life.

In his discussion of the temperature of the Sun, Baur introduced Max Planck's new radiation law that would soon revolutionize physics. However, to Baur and most of his contemporaries Planck's law was primarily of an empirical nature and of interest simply because it represented the spectrum of heat radiation so accurately. He did not mention the hypothesis of energy quantization, which at the time was still disputed or considered unimportant from a physical point of view. Non-quantum presentations of Planck's law were common at the time and appeared in, for example, Arrhenius' *Lehrbuch der kosmischen Physik* published the same year as Baur's *Chemische Kosmographie* (53).

At any rate, Baur's chemical cosmography was an isolated case and not an attempt to create a new framework of cosmic chemistry in the style of cosmical physics. So-called *cosmochemistry* would eventually be established as an extension of geochemistry, but this only happened some four decades later and without Baur having any share in it (54).

Research in Fuel Cells

To the extent that Baur still has a name in the history of science, it is primarily in connection with his systematic work on electrochemical processes in general and fuel cells in particular. In these areas he obtained several patents, including a German patent of 1920 with Treadwell on coal cells with solid electrolytes (DRP 325783), an American patent of 1925 on the recovery of hydrogen and oxygen by electrolysis (US 1543357A) and a Swiss patent of 1939 on a new type of solid fuel cell (CH 204347).

Like a battery, a fuel cell consists of two electrodes separated by an electrolyte, but the fuel cell is continuously supplied with a stream of oxidizer and fuel from which it generates electricity. Unlike the battery, a fuel cell does not run down and it produces electrical energy as long as fuel is supplied. The first devices that converted parts of the chemical energy from fuel and oxidizer (hydrogen and oxygen) into electricity were constructed in the late 1830s, independently by William Groves in England and Christian F. Schönbein in Germany. These early studies were part of the extensive controversy concerning the origin of voltaic electricity, where the chemical theory was confronted by the contact theory (55). Over the next many decades a variety of fuel cells, some of them based on liquids and others on solid electrolytes, were studied, but few of them had any practical applications (56).

Baur's studies of electrochemistry were diverse—they included a model of the electrical organs of fish (57)—but it was only with his and his assistants' work on fuel cells that an extensive and coherent research program was established. As mentioned, as early as 1901, Baur had investigated a nitrogen-hydrogen fuel cell. While at the Braunschweig Technical University he supervised the doctoral dissertation of Itzek Taitelbaum, a Polish student, who studied fuel cells with molten NaOH as electrolyte, various carbon compounds as reactants, and a diaphragm of porous MgO (58).

The ETH laboratory for physical chemistry began research in fuel cells in 1912, when Baur and H. Ehrenberg reported experiments with, for example, molten silver as oxygen cathode and a carbon or iron rod as anode (59). As electrolyte they used various molten salts heated to 1000°C, including KOH, NaOH, $KNaCO_3$, and NaB_4O_7. Over the next two decades Baur and his assistants tried a large number of modifications of fuel cells, claiming in 1921 that they had shown that it was technically feasible to construct stable and powerful cells with electrolytes of molten carbonates (60). However, at the time it was more wishful thinking than reality and it would remain so for

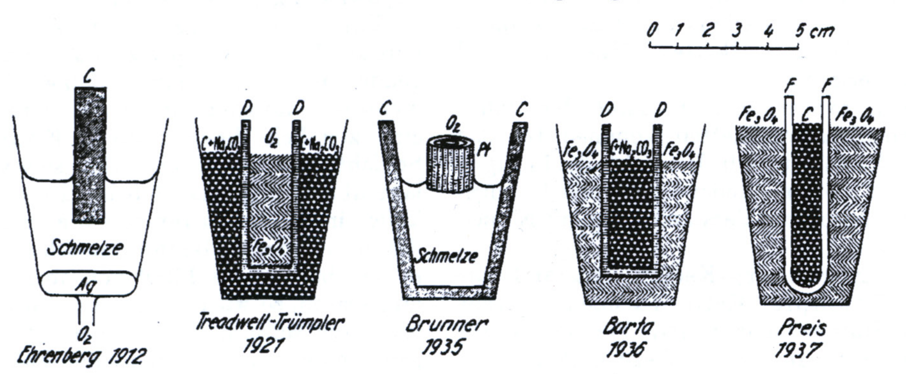

Figure 5. *Various types of coal fuel cells developed in Baur's laboratory. C = coal, D = diaphragm and F = solid state conductor (Festleiter). Source: Ref. 61, p 726.*

decades. Indeed, in his last publication of the subject, a brief review from 1939, Baur admitted that the desired goal, a cell that delivered electric energy with a high efficiency from the heat of combustion, had not been attained. Yet he ended the review in an optimistic tone: "Even when in the end only 50% of the combustion energy of the fuels could be delivered as electric energy at the switchboard of the fuel cell power plant, it would be a revolution in the energy economy of the world" (61).

By the mid-1930s Baur had become convinced that efficient fuel cells must be completely dry. This was one of the conclusions that he reached in a collaborative study with Ronald Brunner on various kinds of cells based on solid conductors (62). In another important paper of 1937, this time in collaboration with Hans Preis, the two ETH chemists reported on a series of experiments on fuel cells with solid electrolytes in the form of ceramic materials with a relatively high conductance (63). They found that the best, if not entirely satisfactory material was a zirconia ceramic with 85% ZrO_2 and 15% Y_2O_3. A substance of this composition is known as the "Nernst-mass" because its conducting properties were first discovered by Nernst, who in the late 1890s used it as a glower in the so-called Nernst lamp (64). Baur and Preis used the Nernst-mass electrolyte or modifications of it in the form of a crucible, and used iron and magnetite (Fe_3O_4) as anode and cathode, respectively. With a stack of eight such cells they constructed a test battery, but although the battery worked, its current output was too low to be of practical significance. Nonetheless, they estimated that the volumetric power density (as measured in kW m^{-3}) was competitive with that of conventional steam power plants.

In spite of not being commercially useful the Baur-Preis cell was an important advance that attracted much attention by later researchers. The paper has received 84 citations in the scientific journal literature (Web of Science), which makes it the most cited of Baur's many papers. Of the 84 citations, 63 date from after 1990. Today zirconia-yttria and zirconia-ceria electrolytes of the kind first studied by Baur and Preis are widely used in fuel cells. Baur and his group at ETH were pioneers in two of the types of fuel cells that currently attract most attention, namely what is known as SOFC (solid oxide fuel cells) and MCFC (molten carbonate fuel cells). These types of high-temperature fuel cells are generally considered the best candidates for the stationary power generation of the future.

Conclusions

Emil Baur was a well-known, respected and productive physical chemist during the first four decades of the twentieth century. Although he was never himself nominated for a Nobel Prize, he nominated several scientists (Table 2). His successful nomination of Francis Aston for the 1922 chemistry prize was particularly important, since it was directly responsible for Aston's prize. Aston's sole nomination for the chemistry prize came from Baur in Zurich, whose motivation was "the discovery of isotopes of ordinary chemical elements by means of the mass spectrograph constructed by F. W. Aston" (65). Several other nominees, including Theodor Curtius, Gustav Tammann, S. P. L. Sørensen, and Georges Urbain, had considerably more support from nominators (66). In 1922 two Nobel prizes were awarded in chemistry, the other to Frederic Soddy who received it for the year 1921. Incidentally, Aston received three nominations for the 1922 *physics* prize.

Table 2. Baur's nominations for the Nobel Prize. Aston was the only one of Baur's nominees who received the prize.

Year	Subject	Nominee	Nationality
1915	chemistry	Eugen Herzfeld	Germany
1922	chemistry	Francis W. Aston	Great Britain
1929	chemistry	Otto Warburg	Germany
1933	physics	Friedrich Paschen; Arnold Sommerfeld	Germany
1934	chemistry	Carl Neuberg	Germany
1939	chemistry	Hermann Staudinger	Germany

Despite his recognition among contemporary scientists, today Baur has fallen into oblivion. The present account of his life and work is naturally limited by existing sources, which seem to be largely missing when it comes to Baur's personal life in particular. Thus I have been unable to find information about his citizenship during his long stay in Switzerland, although I suspect he remained a German citizen. Despite these and other lacunae it is possible to give a picture of the scientific contributions and views of a major player in interwar European physical chemistry. The picture reminds us that a large part of physical chemistry in the period, both in Europe and abroad, was relatively uninfluenced by the new theories of quantum and atomic physics. Classical physical chemistry in the tradition of Ostwald, van 't Hoff and Nernst was still very much alive, but it is a subject that has received little attention by historians of science.

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