

pargylic products exclusively, together with the synthetic mutability of the triple bond combine to make this the method of choice for propargylation.

Many important aspects of this chemistry require additional attention. Perhaps most obviously, complete elucidation of the solution and solid-state structures of the cations 1 (questions 1-3) will give deeper insight into the mode of stabilization provided by the organo-cobalt group. On the synthetic front we foresee great opportunities for stereochemical control based on the special stereoelectronic properties of the -(alkynyl)-Co<sub>2</sub>(CO)<sub>6</sub> unit. Additional tailoring of the characteristics, both steric and electronic, of the cluster core should be possible with various CO-substituted derivatives, e.g., (propargyl)Co<sub>2</sub>(CO)<sub>5</sub>(PR<sub>3</sub>)<sup>+</sup>. New coupling partners for the cations, "third generation" cation complexes, and developments along the lines envisioned above should result in significant new applications in the synthesis of natural and unnatural products. Another newly developing, exciting area of application for the (propargyl)Co<sub>2</sub>(CO)<sub>6</sub><sup>+</sup> cations, and possibly other electrophilic metal  $\pi$ -complexes, is their use to "tag" biomolecules in receptor binding studies and immunology.<sup>74</sup>

One may wonder whether the stabilization of propargylium ions is the exclusive province of cobalt. In-

(74) Jaouen, G.; Vessieres, A.; Top, S.; Ismail, A. A.; Butler, I. S. *J. Am. Chem. Soc.* 1985, 107, 4778.

deed, the answer is no! Reutov and co-workers have reported the isolation of propargylium derivatives of the (C<sub>5</sub>H<sub>5</sub>)<sub>2</sub>M<sub>2</sub>(CO)<sub>6</sub> (M = Mo, W) unit<sup>8</sup> which is isolobal<sup>75</sup> with the -Co<sub>2</sub>(CO)<sub>6</sub> group. While these group VI (6)<sup>76</sup> complexes are inferior to their cobalt relatives in terms of preparative convenience, their reactions have not been examined and may provide new options for selectivity and synthetic utilization. Ultimately, systems for catalytic propargylation eventually may be developed through careful selection of reaction conditions, metal, and auxiliary ligand.

*I am indebted to the enthusiastic efforts of the students, postdocs, and collaborators cited throughout the text. Financial support provided by the National Institutes of Health and the donors of the Petroleum Research Fund, administered by the American Chemical Society, is greatly appreciated. Finally, special gratitude is due to the late Professor Rowland Pettit whose inspirational creativity planted the seed for this chemistry and whose benevolent latitude allowed me to pursue a tangent which ultimately led to the body of work described herein.*

(75) Elian, M.; Chen, M.-L.; Mingos, D. M. P.; Hoffmann, R. *Inorg. Chem.* 1976, 15, 1148. Hoffmann, R. *Angew. Chem., Int. Ed. Engl.* 1982, 21, 711.

(76) In this paper the periodic group notation in parentheses is in accord with recent actions by IUPAC and ACS nomenclature committees. A and B notation is eliminated because of wide confusion. Groups IA and IIA become groups 1 and 2. The d-transition elements comprise groups 3 through 12, and the p-block elements comprise groups 13 through 18. (Note that the former Roman number designation is preserved in the last digit of the new numbering: e.g., III → 3 and 13.)

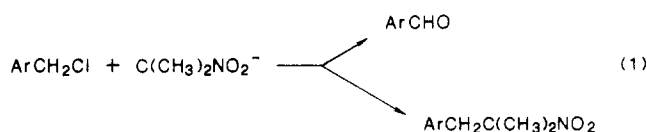
## Electron-Transfer-Induced Chain Reactions and Catalysis. Building Bridges<sup>†</sup> between Inorganic, Organic, and Organometallic Substrates

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The starting point of this presentation is the reaction



for which, in 1964, Kornblum<sup>1</sup> proposed that two concurrent pathways explained the formation of the observed products. The pathway leading to ArCHO is a classical S<sub>N</sub>2 mechanism where the oxygen of the ambident<sup>2</sup> nitronate anion is the nucleophilic center. The second pathway involves an electron transfer from the

nucleophile to ArCH<sub>2</sub>Cl.<sup>1</sup> Kornblum's<sup>3</sup> and Russell's<sup>4</sup> groups defined this second pathway in 1966 by describing a chain mechanism initiated by an electron transfer. A good introduction to the purpose of this presentation may be found in a quotation taken from Kornblum's recent review:<sup>5</sup> "This novel type of substitution at a saturated carbon would constitute an interesting, but somewhat parochial phenomenon, if it were restricted to the alkylation of nitroparaffin salts. But in actuality, electron transfer chain substitutions turn out to be much more general than originally envisaged; new examples constantly are being discovered

<sup>†</sup> We thank Professor R. Hoffmann for allowing us to borrow part of the title of one of his publications (ref 111a).

(1) Kerber, R. C.; Urry, G. W.; Kornblum, N. *J. Am. Chem. Soc.* 1964, 86, 3904.

(2) Kornblum, N.; Lurie, A. P. *J. Am. Chem. Soc.* 1959, 81, 2705.

(3) Kornblum, N.; Michel, R. E.; Kerber, R. C. *J. Am. Chem. Soc.* 1966, 88, 5662.

(4) Russell, G. A.; Danen, W. C. *J. Am. Chem. Soc.* 1966, 88, 5663.

(5) Kornblum, N. In *The Chemistry of Fundamental Groups*; Patai, S., Ed.; Interscience: New York, 1982; Suppl. F, p 361.

Michel Chanon was born in Roannes, France, in 1940. He obtained a State Thesis from the University of Marseille (1967), entered CNRS, and did postdoctoral research on the gear effect in Lund (Sweden) with Professor J. Sandstrom. He was hired as Professor of Chemistry in the Ecole Normale Supérieure de Tunis from 1973 to 1977. Since 1977, he has been Professor of Chemistry at the University of Aix Marseille III. His research topics are electron-transfer-induced reactions, comparison of mechanistic approaches in organic, organometallic, and inorganic reactivities, and computer aids to synthesis.

and it is likely that the surface has only been scratched." In this presentation we shall attempt to answer the question, What is under this surface? In 1978, at the time we entered the field of electron transfer, some groups already had the intuition that the "surface had only been scratched". Their projects were different from ours, however. Indeed, the inspiration for several of their experimental studies was, "Could we demonstrate that many reactions, classically viewed as two-electron types ( $S_N2$ ,  $S_NAr$ , etc.), actually involve a single-electron transfer very rapidly followed by a geminate recombination?" Bilevich,<sup>6</sup> extending Semenov's<sup>7</sup> proposition, had written a provocative review in 1968. Several groups had then designed a series of experiments proposing to give a definite answer to this question.<sup>8-12</sup> We entered the field less ambitiously. Our question was, *Could other elements besides C and Hg be involved in electrophilic substrates entering these electron-transfer chain reactions?* At this time, the main extensions of this type of substitution had been those from  $sp^3$  C to  $sp^2$  C (in aromatic<sup>13a</sup> as well as heteroaromatics<sup>13b</sup>) and to organomercury substrates.<sup>14</sup> The first thing we did in attempting to answer such a question was to use the Science Citation Index. If anyone in inorganic or organometallic chemistry had discovered a reaction having something to do with reaction 1, then that person would doubtless appear in the Citation Index of Kornblum, Russell, or Bunnett. Using this method, we found no such new electrophilic substrate.<sup>15</sup> Apparently, our question had no immediate<sup>16</sup> positive answer. We therefore began to work by following a different course. To extent the field of this kind of substitution required care; Kornblum had warned chemists against overextensions of the basic scheme (see for example ref 20a). A set of recent investigations shows that these words of caution were

(6) Bilevich, K. A.; Okhlobystin, O. Yu *Russ. Chem. Rev. (Engl. Transl.)* 1968, 37, 954. See also: Todres, Z. *Russ. Chem. Rev. (Engl. Transl.)* 1978, 47, 148.

(7) Semenov, N. N. *Some Problems in Chemical Kinetics and Reactivity*; Princeton University Press: Princeton, NJ, 1958.

(8) Bank, S.; Noyd, D. A. *J. Am. Chem. Soc.* 1973, 95, 8203.

(9) Flesia, E.; Crozet, M. P.; Surzur, J. M.; Jauffred, R.; Ghiglione, C. *Tetrahedron* 1978, 34, 1669.

(10) Herbert, E.; Malazeyrat, J. P.; Welwart, Z.; Nadjo, L.; Saveant, J. M. *Nouv. J. Chim.* 1985, 9, 75 and references cited therein.

(11) Tsou, T. T.; Kochi, J. K. *J. Am. Chem. Soc.* 1979, 101, 6319.

(12) Meyers, C. Y.; Matthews, W. S.; Ho, L. L.; Kolb, V. M.; Parady, T. E. In *Catalysis in Organic Synthesis*; Academic: New York, 1977.

(13) (a) Kim, J. K.; Bunnett, J. F. *J. Am. Chem. Soc.* 1970, 92, 7463.

(b) Hay, J. V.; Wolfe, J. F. *J. Am. Chem. Soc.* 1975, 97, 3702.

(14) Russell, G. A.; Hershberger, J.; Owens, K. *J. Am. Chem. Soc.* 1979, 101, 1312.

(15) One noticeable exception is provided by the reaction of (2-methoxyallyl)nickel bromide with 2-octyl iodide. Hegedus, L.; Stiverson, R. K. *J. Am. Chem. Soc.* 1974, 96, 3250. See also: Hegedus, L.; Thompson, D. H. P. *J. Am. Chem. Soc.* 1985, 107, 5663.

(16) A referee remarked that in 1978 both Feldberg's (ECE in  $Cr(CN)_6^{3-}$  substitution)<sup>17</sup> and Saveant's (ECE in  $p-CH_3COC_6H_4X^{18}$ ) works were well-known in electrochemical circles. That the connection between inorganic and organic substrates was far from obvious is shown, however, by the following facts: (1) Ebersson (well-known electrochemist), in his review article on electron transfer,<sup>19</sup> devotes an entire section to the gap existing between inorganic and organic views of electron transfer. (2) In the best available reviews<sup>20,21</sup> published at that time on  $S_{RN}1$  type processes, no mention was made of inorganic anteriority in the field of electron-provoked reactions. (3) In the best available reviews<sup>22,23</sup> dealing with electron-transfer reactions and written by inorganic chemists, the same situation prevailed with, this time, silence about  $S_{RN}1$  and related organic processes.

(17) Feldberg, S. W.; Jeftic, L. *J. Phys. Chem.* 1972, 76, 2439.

(18) Pinson, J.; Saveant, J. M. *J. Chem. Soc., Chem. Commun.* 1974, 934.

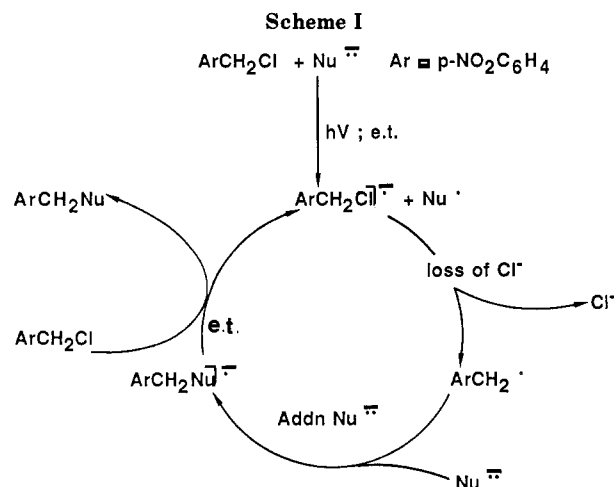
(19) Ebersson, L. *Adv. Phys. Org. Chem.* 1982, 18, 79.

(20) Kornblum, N. *Angew. Chem., Int. Ed. Engl.* 1975, 14, 734; (a) see note at bottom of p 744.

Table I.  
Experimental Earmarks Shared by Reactions 1 and 2<sup>a</sup>

experimental facts	ref
1. photostimulation with $\Phi > 1$	30, 34, 35
2. scavenging by oxidizing agents	30
3. entrainment by reducing agents	32, 33a
4. paramagnetic intermediates observed in the reaction medium	35-39
5. charge-transfer complexes between some couples of reagents	33b

<sup>a</sup> For more details see ref 25, Table 2.



to be taken seriously: several reactions where an electron-transfer mechanism had been proposed as the primary act of reaction have proved to be probably deceptive.<sup>24</sup> Therefore, the first thing to do was to select the experimental results which had led the pioneers in the field to propose a new mechanistic scheme. Such data are gathered in Table 1 of ref 25.

On the other hand, my teaching in inorganic chemistry was mechanistically<sup>26-28</sup> oriented, and having realized the M. Tobe was favorable to unifying views in chemistry,<sup>29</sup> I asked him for permission to work with him at the foregoing project during the summer of 1979. He accepted; these were two marvelous months of learning, discovery, and exciting discussions with Prof. Tobe.

### An Early Inorganic Analogue of *p*-Nitrobenzyl Halide Substrates

With our objective in mind, I began to search through the inorganic chemistry literature. I finally discovered

(21) Bunnett, J. F. *Acc. Chem. Res.* 1978, 11, 413.

(22) Linck, R. G. In *Transition Metals in Homogeneous Catalysis*; Schrauzer, G. N., Ed.; Marcel Dekker: New York, 1971; p 297.

(23) Cannon, R. D. *Electron Transfer Reactions*; Butterworths: London, 1980.

(24) (a) Newcomb, M.; Burchill, M. T. *J. Am. Chem. Soc.* 1984, 106, 2450. (b) Newcomb, M.; Burchill, M. T. *J. Am. Chem. Soc.* 1984, 106, 8276. (c) Huzthy, P.; Lempert, K.; Simig, G.; Tamas, J. *J. Chem. Res. Synop.* 1985, 309. (d) Vacher, B.; Samat, A.; Chanon, M. *Tetrahedron Lett.* 1985, 26, 5129. (e) Bailey, W. F.; Patricia, J. J.; Nurmi, T. T.; Wang, W. *Tetrahedron Lett.* 1986, 27, 1861. (f) Ebersson, L.; Larsson, B. *Acta Chem. Scand. Ser. B* 1986, 40, 210.

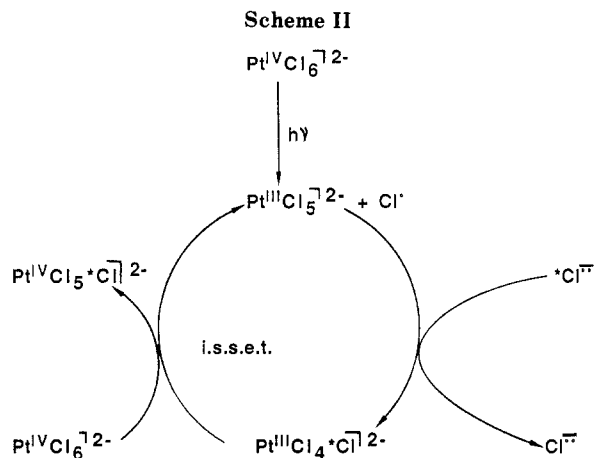
(25) Chanon, M.; Tobe, M. L. *Angew. Chem., Int. Ed. Engl.* 1982, 21, 1. (a) p 10, (b) p 11.

(26) Purcell, K. F.; Kotz, J. C. *Inorganic Chemistry*; Saunders: Philadelphia, PA, 1977.

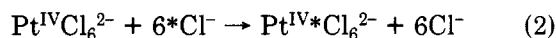
(27) Tobe, M. L. *Inorganic Reaction Mechanisms*; Nelson, T. and Sons: Sunbury on Thames Middlesex, U.K., 1976.

(28) Wilkins, R. G. *The Study of Kinetics and Mechanisms of Reactions of Transition Metal Complexes*; Allyn and Bacon: Boston, MA, 1974.

(29) Tobe, M. L. In the preface of *Reaction Mechanisms in Inorganic Chemistry*; Butterworths University Park Press: London, 1972; Ser. 1, Vol. 9.



a possible candidate for the extension of the electron-transfer-induced chain substitution mechanism. This was associated with the radiochloride exchange of ligands in  $\text{PtCl}_6^{2-}$  (25 °C, in water):



In this reaction, reagents and products are all diamagnetic, as is the case in reaction 1. Furthermore, to explain the experimental behavior of this reaction, Taube<sup>30</sup> in 1954 proposed a chain reaction involving  $\text{Pt}^{\text{III}}$  intermediates. These intermediates, with their  $d^7$  configuration, are clearly radical-like. The experimental features displayed by this reaction are strikingly reminiscent of those associated with reaction 1. Table I lists the most notable analogies. We were surprised to encounter a reaction which had been studied with much more elaborate techniques (pulse radiolysis<sup>38</sup> and flash photolysis,<sup>35</sup> for example) than had been used for reaction 1. For 25 years, excellent inorganic and organic teams *working in the same field of electron-transfer reactions had simply overlooked each other's contributions*. Ebersson independently reached the same conclusion when he attempted to extend Marcus theory to organic substrates.<sup>19</sup> We were, therefore, in an interesting epistemological situation: two groups of chemists had observed similar experimental data in two different reaction systems. Did they reach the same mechanistic conclusion? The answer is “no”, but this “no” leads to interesting cross-fertilization. Let us first consider the main mechanistic differences associated with the schemes proposed by Kornblum–Russell and Taube for these substitution reactions (Schemes I and II, respectively).

There are two main differences, one in the initiation step and one in the propagation step. In the initiation

(30) Rich, R. L.; Taube, H. *J. Am. Chem. Soc.* **1954**, *76*, 2608.

(31) Messing, A. F. Ph.D. Dissertation, Northwestern University, Evanston, IL, 1957. We thank Prof. F. Basolo for providing a copy of this unpublished work.

(32) Poe, A. J.; Vaidya, M. S. *J. Chem. Soc.* **1961**, 2981.

(33) (a) Poe, A. J.; Vaidya, M. S. *J. Chem. Soc.* **1960**, 187. (b) Poe, A. *J. Discuss. Faraday Soc.* **1960**, *29*, 133.

(34) Dreyer, R.; König, K.; Schimdt, H. *Z. Phys. Chem. (Leipzig)* **1964**, *227*, 257.

(35) Adamson, A. W.; Sporer, A. H. *J. Am. Chem. Soc.* **1958**, *80*, 3865.

(36) Wright, R. C.; Laurence, G. S. *J. Chem. Soc., Chem. Commun.* **1972**, 132.

(37) Adams, G. E.; Broszkiewicz, R. B.; Michael, B. D. *Trans. Faraday Soc.* **1968**, *64*, 1256.

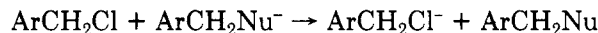
(38) Storer, D. K.; Waltz, W. L.; Brodovitch, J. C.; Eager, R. L. *Int. J. Radiat. Phys. Chem.* **1975**, *7*, 693.

(39) Brodovitch, J. C.; Storer, D. K.; Waltz, M. L.; Eager, R. L. *Int. J. Radiat. Phys. Chem.* **1976**, *8*, 465.

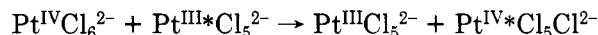
step, Taube interpreted the “accelerating diffuse daylight effect as a light-induced homolytic cleavage of the  $\text{Pt}^{\text{IV}}\text{—Cl}$  bond in an electronically excited  $\text{Pt}^{\text{IV}}\text{Cl}_6^{2-}$ . Kornblum and Russell probably would explain the role of “diffuse daylight” by a light-enhanced redox relationship<sup>58b</sup> between the nucleophile and the electrophile, rendering the formation of the radical anion of the electrophile easier. The bond dissociation enthalpy of  $\text{C—Cl}$ ,<sup>40</sup> the photochemical behavior of benzyl chloride,<sup>41,42</sup> and the possible observation of charge-transfer complexes (CTC)<sup>43</sup> converge to suggest that for reaction 1 the role of light is to enhance the redox relationship<sup>58b</sup> of the nucleophile–electrophile couple. For reaction 2 the MO diagram<sup>44</sup> of  $\text{PtCl}_6^{2-}$  backs the possibility of a homolytic dissociation<sup>45</sup> as does the general remark that quenching of excited states by halide ions usually takes place via energy transfer instead of electron transfer.<sup>46–49</sup>

The light-enhanced redox relationship is, however, backed by experimental data<sup>50</sup> which show that, in its excited state,  $\text{PtCl}_6^{2-}$  is oxidizing enough to oxidize  $\text{SO}_4^{2-}$ ,  $\text{Cl}^-$ , and  $\text{Br}^-$ .  $X\alpha$  calculations<sup>51,52</sup> of the paramagnetic intermediates involved in the mechanism show the difficulty of attributing unambiguously a structure to the experimentally<sup>35,37,38</sup> observed transients. Noting that the radical anions of *p*-nitrobenzyl halides<sup>53</sup> have never been observed directly in the reaction between a nucleophile and *p*-nitrobenzyl halides, we are obliged to state that the inorganic and organic mechanistic hypotheses are about equal with regard to firm experimental evidence concerning the initiation step.

Let us now turn our attention to the propagation step. For the organic case it involves the following



and for the inorganic example, it involves



Here, again, *an important difference between the organic and inorganic approaches to electron transfer appears*. The inorganic approach clearly distinguishes two main kinds of electron-transfer mechanisms: outer sphere and inner sphere.<sup>23,54–56</sup> We have discussed

(40) Vogel, P. *Carbocation Chemistry*; Elsevier: Amsterdam, 1985; Table 1.5.

(41) Cristol, S. J.; Bindel, T. H. *J. Org. Chem.* **1980**, *45*, 95.

(42) Lodder, G. In *The Chemistry of Halides, Pseudo Halides and Azides*; Patai, S., Rappoport, Z., Eds.; Interscience: New York, 1983; Suppl. D, Part 1, p 1605.

(43) Julliard, M.; Scagliarini, J. P.; Rajzmann, M.; Chanon, M. *Chimia* **1986**, *40*, 16.

(44) Goursot, A.; Penigault, E.; Chermette, H. *Chem. Phys. Lett.* **1983**, *97*, 215.

(45) Rehorek, D.; Dubosc, C. M.; Jansen, E. G. *Inorg. Chim. Acta* **1984**, *83*, 147.

(46) Ebersson, L. *Acta Chem. Scand., Ser. B* **1984**, *38*, 439.

(47) Watkins, A. R. *J. Phys. Chem.* **1974**, *78*, 2555.

(48) Treinin, A.; Hayon, E. *J. Am. Chem. Soc.* **1976**, *98*, 3884.

(49) Watkins, A. R. *J. Phys. Chem.* **1974**, *78*, 1885.

(50) (a) Shagisultanova, G. A.; Karaban, A. A.; Poznyak, A. L. *Khim. Vys. Energ.* **1971**, *5*, 368; *High Energy Chem. (Engl. Transl.)* **1972**, *6*, 333.

(b) Cox, L. E.; Peters, D. G.; Wehry, E. L. *J. Inorg. Nucl. Chem.* **1972**, *34*, 297. (c) Shul'pin, G. B.; Nizova, A. T. *J. Organomet. Chem.* **1984**, *276*, 115.

(51) Goursot, A.; Chermette, H.; Penigault, E.; Chanon, M.; Waltz, W. L. *Inorg. Chem.* **1984**, *23*, 3618.

(52) Goursot, A.; Chermette, H.; Chanon, M.; Waltz, W. L. *Inorg. Chem.* **1985**, *24*, 1042.

(53) Neta, P.; Behar, D. *J. Am. Chem. Soc.* **1980**, *102*, 4798.

(54) Taube, H. *J. Chem. Educ.* **1986**, *45*, 452.

Table II<sup>a,b</sup>

propagation	initiation		
	o.s.e.t.	i.s.e.t. without atom transfer	i.s.e.t. with atom transfer
o.s.e.t.	1 (= S <sub>NR</sub> 1)	2	3
i.s.e.t. without atom transfer	4	5	6
i.s.e.t. with atom transfer	7 (= Taube)	8	9

<sup>a</sup> See ref 58a and 61 for possible examples of each case. <sup>b</sup> o.s.e.t. represents outer-sphere electron transfer, and i.s.e.t. represents inner-sphere electron transfer.

elsewhere<sup>57b,58a</sup> the correspondence of inner-sphere electron transfer with the bimolecular homolytic scheme (S<sub>H</sub>2).<sup>59</sup> We wish to stress here that the inorganic nomenclature introduced by Taube is particularly powerful.<sup>54</sup> Indeed, applying it naturally to organic substrates, we proposed in 1982 that S<sub>N</sub>2 could be viewed as an inner-sphere electron transfer in which carbon plays the role of the bridge.<sup>61b</sup> Pross and Shaik recently reached the same conclusion through application of the configuration mixing (CM) model.<sup>62,63</sup> We will, however, no longer deal with this question here; indeed, the possibility of a continuum between inner-sphere and outer-sphere electron-transfer processes raises fundamental questions about the geometries of the transition states<sup>64</sup> and the timing of bond formation. These questions would require a specific report by themselves. With this nomenclature difference in mind, one sees that the propagation step in the *p*-nitrobenzyl chloride case is outer-sphere,<sup>65</sup> whereas the Pt<sup>IV</sup>Cl<sub>6</sub><sup>2-</sup> case involves an inner-sphere electron transfer for the propagation step. This leads to an important consequence in the conception of this general class of chain substitutions. As all these processes contain at least two steps in which an electron transfer may take place, there should be at least nine general types of such reactions, as illustrated in Table II. ("At least" stands because Table II does not include chain reactions in which the propagation step is an electron transfer and the initiation is a homolysis.)

This is somewhat to be expected: *when a reaction is considered in its entirety, it usually contains subclasses which describe variations within the general scheme.*

### The Inorganic Counterpart of S<sub>RN</sub>1 Aromatic Reactivity

So this comparison of PtCl<sub>6</sub><sup>2-</sup> with *p*-NO<sub>2</sub>C<sub>6</sub>H<sub>4</sub>CH<sub>2</sub>Cl provides a rich harvest of fresh views on the inorganic as well as on the organic side. But this is not all: if the

(55) Taube, H.; Gould, E. S. *Acc. Chem. Res.* 1969, 2, 321.

(56) Haim, A. *Acc. Chem. Res.* 1975, 8, 265.

(57) Julliard, M.; Chanon, M. *Chem. Rev.* 1983, 83: (a) p 425, (b) p 431, (c) pp 456-458, (d) p 456, (e) p 487, (f) p 461, (g) p 464, (h) p 463, (i) p 478.

(58) (a) Julliard, M.; Chanon, M. *Chem. Scr.* 1984, 24, 11. (b) Julliard, M.; Chanon, M. *Chem. Br.* 1982, 18, 558.

(59) Ingold, K. U.; Robert, B. P. *Free Radical Substitution Reactions*; Wiley: New York, 1971. For an electron-transfer alternative to S<sub>H</sub>2 on metallic centers,<sup>60</sup> see ref 25, p 10.

(60) Davies, A. G.; Roberts, B. P. In *Free Radical in Chemistry*; Kochi, J. K., Ed.; Wiley: New York, 1973; Vol. I, p 547.

(61) Chanon, M. *Bull. Soc. Chim. Fr.* 1982: (a) p 197, (b) p 216.

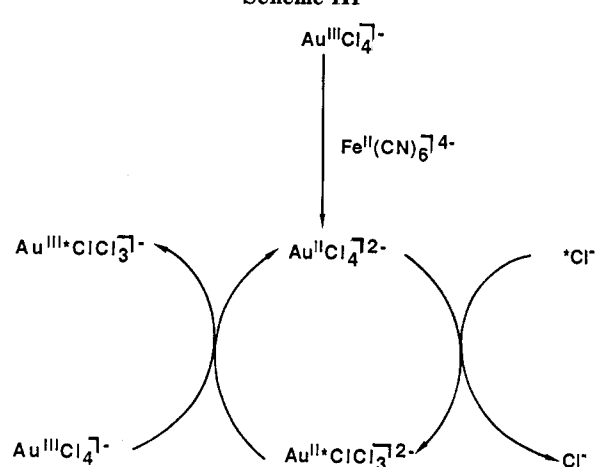
(62) Pross, A. *Acc. Chem. Res.* 1985, 18, 212.

(63) Pross, A.; Shaik, S. *Acc. Chem. Res.* 1983, 16, 363.

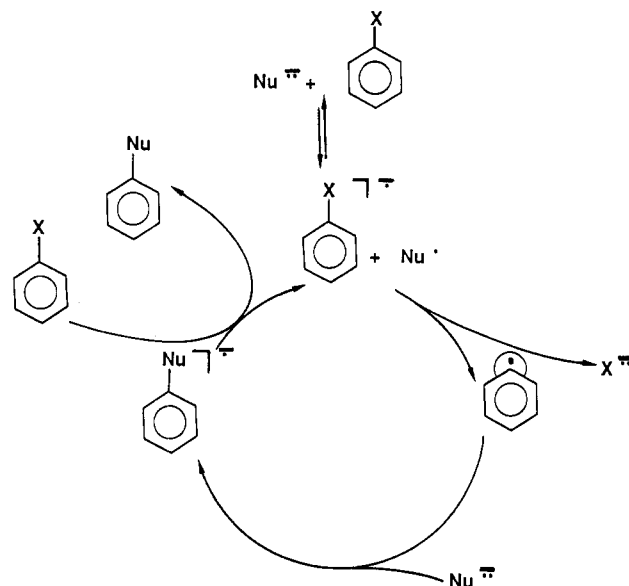
(64) (a) Berg, U.; Gallo, R.; Metzger, J.; Chanon, M. *J. Am. Chem. Soc.* 1976, 98, 1260. (b) Berg, U.; Gallo, R. *Acta Chem. Scand., Ser. B* 1983, 37, 661.

(65) Unless one can prove that there is a strong CTC between the oxidizing and reducing species in the propagation step (see ref 61, p 199).

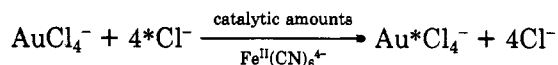
Scheme III



Scheme IV



octahedral Pt<sup>IV</sup> complexes can parallel the sp<sup>3</sup> carbon of benzyl halides, what will parallel the behavior of haloaromatics discovered by Bunnett?<sup>13a,21</sup> Square-planar transition-metal complexes of appropriate configuration could be compared with the foregoing aromatics. Here again the inorganic case was discovered long before its organic analogue. In 1954, Taube reported that the exchange reaction<sup>66</sup>

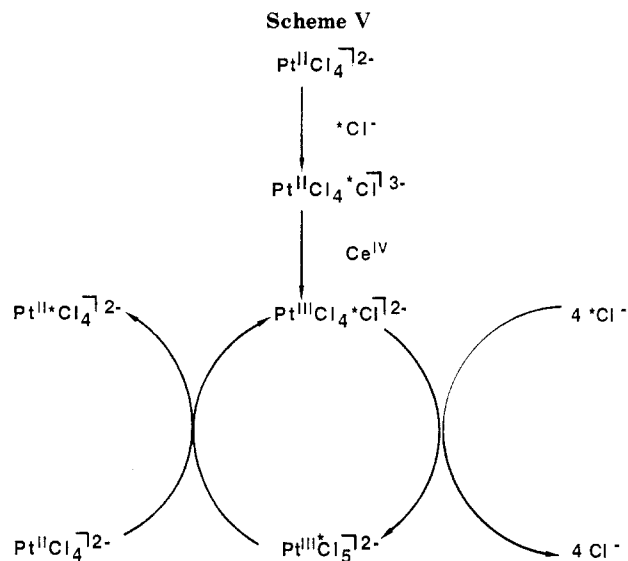


was greatly accelerated by addition of catalytic amounts of Fe<sup>II</sup>(CN)<sub>6</sub><sup>4-</sup> (turnovers of 10<sup>4</sup> <sup>36</sup>Cl<sup>-</sup> per Fe). However, light did not accelerate the reaction. This fact is noteworthy. A strict application of the criteria given in Table I would say that this reaction is not of the S<sub>RN</sub>1 type. This lack of photostimulation is apparently also true<sup>57d</sup> for most of the inorganic examples given in reviews<sup>22</sup> or textbooks<sup>26-28</sup> dealing with electron-transfer-catalyzed and electron-transfer-induced chain reactions.

The mechanism proposed by Taube approximately parallels the S<sub>RN</sub>1 mechanism (Schemes III and IV).

The main difference lies in the substitution step, which is associative in Au<sup>II</sup>Cl<sub>4</sub><sup>2-</sup> but clearly dissociative

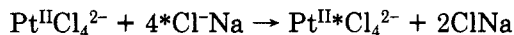
(66) Rich, R. L.; Taube, H. *J. Phys. Chem.* 1954, 58, 6.



in the  $S_{RN}1$  mechanism. One could envision the  $Au^{II}Cl_4^{2-}$  mechanism as an  $S_{RN}2$  mechanism.<sup>67</sup> The MO diagram of  $Au^{III}Cl_4^-$ , where the LUMO is of  $\sigma^*$  antibonding character,<sup>68,69</sup> suggests however that an  $S_{NR}1$  mechanism could also be defended.

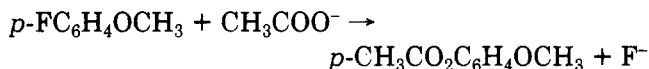
### The Inorganic Precursor of $S_{ON}2$

There was more to be harvested in the inorganic field of electron transfer. In all the foregoing examples, the substitution reactions were made easier by addition of an electron to the substrate. *But what about oxidatively induced substitutions?* Here, again, Taube's reports provided an early answer with the reaction<sup>30</sup>



A solution of  $Pt^{II}Cl_4^{2-}$  (0.0125 M) in the presence of NaCl (0.0342 M) and  $HNO_3$  (0.062 M) undergoes 1% exchange with radioactive chloride in 30 min at 0 °C. Addition of catalytic amounts of  $Ce^{IV}$  ( $5.5 \times 10^{-4}$  M) results in 87% exchange in 4 min. The proposed mechanism<sup>70</sup> is shown in Scheme V.

In 1980, Ebersson and Jönsson<sup>71</sup> discovered the anodically induced substitution



They proposed the mechanism shown in Scheme VI.

A comparison of the two mechanisms suggests that these are variations around a general scheme.<sup>70</sup> More quantitative data on the reactivities of transients would allow the placement of every case in perspective with Table II. Waltz is presently performing such in-depth studies on  $Pt^{III}$  transients.<sup>72</sup>

(67) (a) Russell, G. A.; Mudryk, B.; Ros, F.; Jawdoskiuk, M. *Tetrahedron* 1982, 38, 1059. (b) Russell, G. A.; Mudryk, B.; Ros, F.; Jawdoskiuk, M. *J. Am. Chem. Soc.* 1981, 103, 4610.

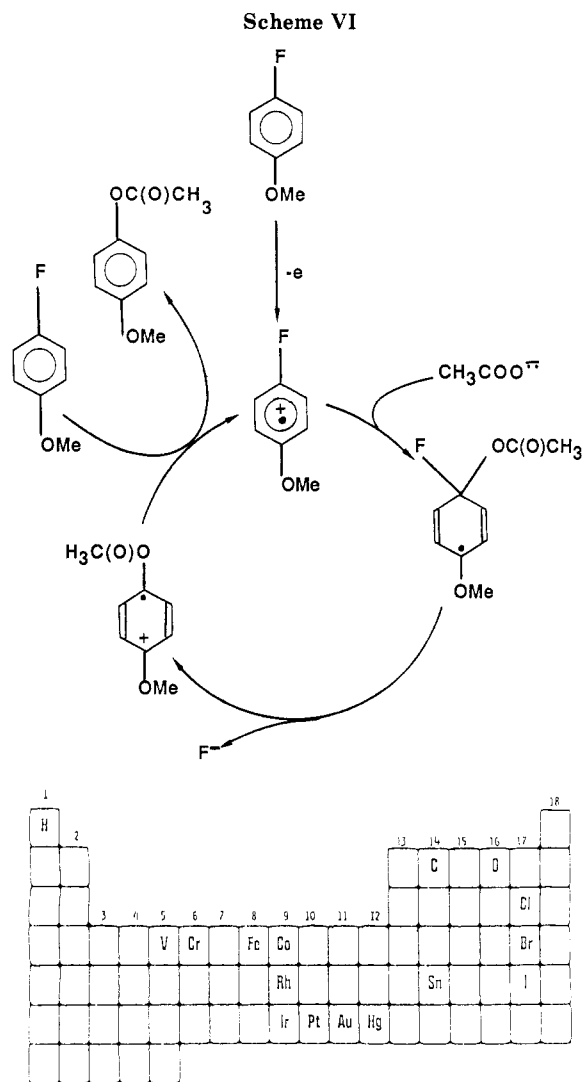
(68) Goursot, A., personal communication.

(69) Sakaki, S.; Hagiwara, N.; Iwasaki, N.; Ohyoshi, A. *Bull. Chem. Soc. Jpn.* 1977, 50, 14.

(70) This mechanism is only one out of several proposed as possibilities in ref 22; the reader is urged to return to the original report to make his own opinion.

(71) (a) Ebersson, L.; Jönsson, L. *J. Chem. Soc., Chem. Commun.* 1980, 1187. (b) Ebersson, L.; Jönsson, L.; Wistrand, L. G. *Tetrahedron* 1982, 38, 1087.

(72) (a) Khan, H. M.; Waltz, W. L.; Woods, R. J.; Lilie, J. *Can. J. Chem.* 1981, 59, 3319. (b) Khan, H. M.; Waltz, W. L.; Lilie, J.; Woods, R. J. *Inorg. Chem.* 1982, 21, 1489.



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
H					V	Cr	Fe	Co					C	O			
								Rh						Sn		Br	
								Ir	Pt	Au	Hg					I	

**Figure 1.** Role of electron-transfer catalysis (ETC) in chemistry. Only elements engaged in complexes or molecules directly activated by ETC are displayed. Relevant references for every element may be found in Table XIV of ref 57.

### Other Elements Involved. The Extension to Organometallics

The foregoing examples provide a quite positive answer to our initial question. We can now add  $Pt^{IV}$ ,  $Pt^{II}$ , and  $Au^{III}$  to C and Hg; but in fact, they are only a small part of a far richer harvest, as shown in Figure 1, in which are added other elements found in the inorganic literature.

A simple application of the angular overlap model<sup>26,73</sup> provides some hints<sup>25</sup> about which elements involved in hexacoordinated complexes should be prone to activation induced by electron transfer.

The literature suggested at this time that some oxidative additions<sup>74</sup> and other organometallic chain reactions<sup>75</sup> were strangely reminiscent of  $S_{RN}1$  type processes. We therefore mailed a copy of our manuscript to Dr. Kochi in Dec. 1979, and he kindly invited us to

(73) (a) Burdett, J. K. *Molecular Shapes*; Wiley: New York, 1980. (b) Gerloch, M.; Wooley, R. G. *Prog. Inorg. Chem.* 1984, 31, 371.

(74) Osborn, J. A. In *Organotransition Metal Chemistry*; Ishii, Y., Tsutsui, M., Eds.; Plenum: New York, 1975; p 65. Compare with: Elson, I. H.; Morrell, D. G.; Kochi, J. K. *J. Organomet. Chem.* 1975, 84, C7.

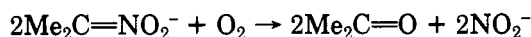
(75) (a) Hoffman, N. W.; Brown, T. L. *Inorg. Chem.* 1978, 17, 613. (b) Absi Halabi, M.; Brown, T. L. *J. Am. Chem. Soc.* 1977, 99, 2982. (c) Butts, S. B.; Shriver, D. F. *J. Organomet. Chem.* 1979, 169, 191.

Bloomington to explore more thoroughly the implications of electron-transfer-induced reactions in organometallic reactivity.<sup>61</sup> This aspect of electron-transfer-initiated reactions is the one which has undergone the most drastic developments during these past 5 years and is too extensive for treatment here. Sufficient is to say that electron-transfer catalysis has been shown to be involved in mononuclear organometallics [(CO)<sub>3</sub>Re(phen)CH<sub>3</sub>CN<sup>+</sup>,<sup>76</sup> LM(CO)<sub>n</sub> with M = W, Mo, Mn,<sup>77</sup> (η<sup>5</sup>-Cp)(CO)<sub>2</sub>Fe(2-norbornyl),<sup>78a</sup> *cis*-H(CH<sub>3</sub>)Os(CO)<sub>4</sub><sup>79</sup>] as well as in binuclear ones [(CO)<sub>5</sub>ReRe(CHO)CO<sub>4</sub><sup>-</sup>,<sup>80</sup> Rh<sub>2</sub>(diisocyanopropane)<sub>4</sub><sup>2+</sup><sup>81</sup>] and in clusters [Co<sub>2</sub>(μ-RCCR)(CO)<sub>6</sub>,<sup>82</sup> capped clusters CoCo<sub>3</sub>, SCo<sub>3</sub>, SCo<sub>2</sub>Fe,<sup>83</sup> Co<sub>4</sub>(CO)<sub>9</sub>tripod,<sup>84</sup> (μ-alkoxymethane-thione-C,S)-(methylthio)(1,1,1,2,2,2-hexacarbonyl)di-iron,<sup>85</sup> Fe<sub>3</sub>(CO)<sub>9</sub>(μ-3-PPh)<sub>2</sub>,<sup>86a</sup> Co<sub>4</sub>(CO)<sub>10</sub>(PPh)<sub>2</sub>,<sup>86b</sup>]. Several recent reviews cover this field.<sup>87</sup>

### Many Other Transformations beyond Substitution

While discussing the inorganic literature with M. L. Tobe, he indicated to me an interesting suggestion by Gillard concerning the stereoisomerization reaction.<sup>88</sup> This author suggested that the crucial step in the mechanism was the transformation of Co<sup>III</sup>(inert) into Co<sup>II</sup> by the catalyst, thus allowing a far more facile ligand exchange and stereoisomerization. This was a strong hint that, *beyond substitution reactions, other transformations were relevant to the concept that had been our starting point.*

On the organic side, in 1971 Kornblum<sup>89</sup> had shown that an elimination reaction was triggered by an electron transfer from PhS<sup>-</sup> to NO<sub>2</sub>-C(Me)<sub>2</sub>C(Me)<sub>2</sub>-NO<sub>2</sub>. In 1954, Russell<sup>90</sup> had proposed an electron-transfer chain reaction for base catalyzed autoxidations:



(76) Summers, D. P.; Luong, J. C.; Wrighton, M. S. *J. Am. Chem. Soc.* **1981**, *103*, 5238.

(77) (a) Hershberger, J. W.; Klinger, R. J.; Kochi, J. K. *J. Am. Chem. Soc.* **1982**, *104*, 3034. (b) Zizelman, P. M.; Amatore, C.; Kochi, J. K. *J. Am. Chem. Soc.* **1984**, *106*, 3771.

(78) (a) Bly, R. S.; Silverman, G. S.; Bly, R. K. *Organometallics* **1985**, *4*, 374. (b) Touchard, D.; Lelay, C.; Fillaut, J. L.; Dixneuf, P. H. *J. Chem. Soc., Chem. Commun.* **1986**, 37.

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(82) Bezems, G. J.; Rieger, P. H.; Visco, S. J. *J. Chem. Soc., Chem. Commun.* **1981**, 265.

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(b) Lhadi, E. R.; Mahé, C.; Patin, H.; Darchen, A. *J. Organomet. Chem.* **1983**, *246*, C61.

(86) (a) Ohst, H. H.; Kochi, J. K. *J. Am. Chem. Soc.* **1986**, *108*, 2897.

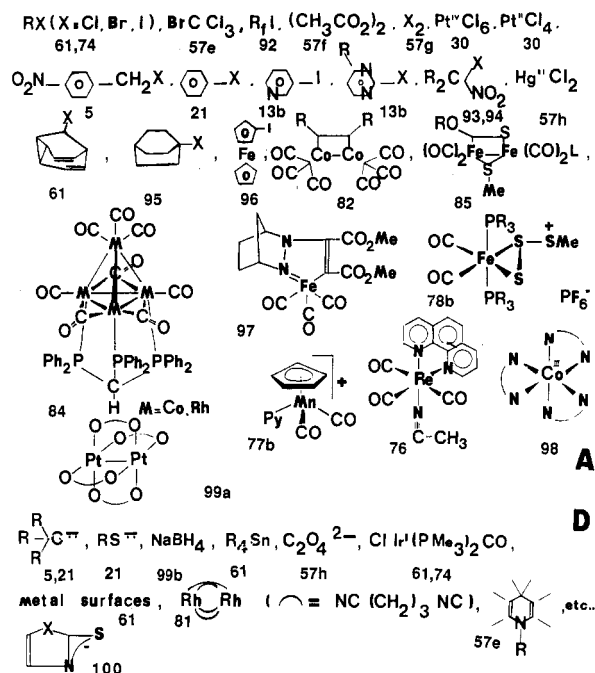
(b) Richmond, M. R.; Kochi, J. K. *Inorg. Chem.* **1986**, *25*, 656.

(87) (a) Brown, T. L. *Ann. N.Y. Acad. Sci.* **1980**, *333*, 80. (b) Albers, M. O.; Coville, N. J. *Coord. Chem. Rev.* **1984**, *53*, 227. (c) Connelly, N. G.; Geiger, W. E. *Adv. Organomet. Chem.* **1984**, *23*, 2. (d) Geiger, W. E.; Connelly, N. G. *Adv. Organomet. Chem.* **1985**, *24*, 87. (e) Halpern, J. *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 276. (f) Stigman, A. E.; Tyler, D. R. *Comments Inorg. Chem.* **1986**, *5*, 215.

(88) Gillard, R. D. *J. Chem. Soc. A* **1967**, 917.

(89) Kornblum, N.; Boyd, S. D.; Pinnick, H. W.; Smith, R. G. *J. Am. Chem. Soc.* **1971**, *93*, 4316.

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**Figure 2.** Variety of structures involved in electron-transfer catalysis (ETC). Top structures (A) are behaving as electrophilic substrates in the DA interaction. Bottom structures (D) are behaving as nucleophiles.

We therefore began the search for other transformations displaying the experimental properties that we have encountered throughout this presentation.

To make a long story short, we can state that we found many candidates. We are not certain that all the examples gathered in ref 57 are beyond all doubt actual examples, because, for a long time, the experimental criteria adopted in the literature to recognize an electron-transfer reaction have been rather loose; when the electron-transfer component was recognized, it was often given without further discussion concerning its chain vs. nonchain character.<sup>25a</sup> However, they were gathered to show in which directions further experimental work could extend this field and extract correspondences<sup>91</sup> between photochemistry, electrochemistry, and "ordinary" chemistry.

The wide scope of the concept is shown by the number of transformations that it covers: *substitutions, cycloadditions, sigmatropic rearrangements, isomerizations, polymerizations, oxidations, reductions, oxidative additions, addition-elimination, diazo transfer, reductive eliminations, α-eliminations, Diels-Alder, enantiomerizations, stereoisomerizations, rearrangements.* Even more impressive is Figure 2, which shows the variety of structures involved. Beyond any doubt,

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(92) Feiring, A. E. *J. Fluorine Chem.* **1984**, *24*, 191.

(93) Bowman, W. R.; Rakshit, D.; Valmas, M. D. *J. Chem. Soc., Perkin Trans. 1* **1984**, 2327.

(94) Russell, G. A. *Adv. Phys. Org. Chem.* **1987**, *23*, 271.

(95) Rossi, R. A.; Palacios, S. A.; Santiago, A. N. *J. Org. Chem.* **1982**, *47*, 4654.

(96) Fox, M. A.; Ranade, A. C.; Madany, I. *J. Organomet. Chem.* **1982**, *239*, 269.

(97) Estevan, F. R.; Lahuerta, P.; Latorre, J. *Inorg. Chim. Acta* **1986**, *116*, L33.

(98) Geselowitz, D. A.; Taube, H. *Inorg. Chem.* **1981**, *20*, 4036.

(99) (a) Roundhill, M. *J. Am. Chem. Soc.* **1985**, *107*, 4354. (b) Grove, J. T.; Ma, K. W. *J. Am. Chem. Soc.* **1974**, *96*, 6527.

(100) Meyer, M.; Samat, A.; Chanon, M. *Heterocycles* **1986**, *24*, 1013.

we are dealing with a quite general phenomenon.

### A Symmetrical Role for the Proton and the Electron in Catalysis?

It is one thing to recognize a phenomenon as general but quite another to place it in perspective with the body of accepted knowledge. When we initiated the work, we were fascinated by *the variety of activations associated with these processes*.<sup>25b</sup> Indeed, substrates such as *p*-nitro cumyl halides or unsubstituted aromatic halides were induced to react under very mild conditions,<sup>20,21</sup> the longer we worked, *the more we were attracted by the symmetry between the roles played by the proton and the electron*.<sup>101</sup>

However, the role of the proton is recognized as typically catalytic whereas many of the previously described  $S_{RN}1$  reactions would be classified rather under the heading of chain reactions. The term "chain reaction" has been defined by IUPAC in physical organic chemistry,<sup>102</sup> and the term "catalysis" has been defined by IUPAC both in physical organic chemistry and in colloid and surface chemistry.<sup>103</sup> The definition given by the second insists more on some analogies between chain and catalytic reactions. To check whether the relationship between catalysis and chain reactions was unanimously perceived by chemists involved in different aspects of catalysis, we sent a questionnaire to experts in the field. The answers were grossly divided into two groups: one favoring the relationship found in classical textbooks (some reactions may be classified as both chain or catalytic, and the other not); another one, more kinetically oriented,<sup>104</sup> preferred the relationship "if a reaction pertains to the class of catalytic reactions it is necessarily a chain reaction, but the reverse is not true". This set of answers clearly shows that the border between chain and catalytic reactions is not clearly delineated. In our opinion, this situation is strongly reminiscent of the earlier controversies<sup>105</sup> associated with the definitions of acids as opposed to electron pair acceptors (Lewis acids). Within such an analogy, classical catalytic reactions and chain reactions could be viewed as subparts of a class of reactions defined as generalized catalysis. Generalized catalysis makes the parallel catalytic roles of the electron and the proton become more natural.

Whatever the fate reserved to this proposition (as Gillespie<sup>105</sup> pointed out for the acid-base case, the most important point is not so much how we christen the things but the fact that analogies stimulate new valuable experimental work), what is actually important is that there is a *very general class of reactions pervading organic, inorganic, and organometallic chemistries*. Furthermore, it involves correspondences<sup>91</sup> between photochemistry, electrochemistry,<sup>106</sup> and "ordinary" chemistry. This class deserves a specific treatment because it has provided chemists with a bunch of new

reactions<sup>5,21,94,107-110</sup> during the past decade. We believe that the fundamental studies performed on inorganic electron-transfer reactions<sup>23</sup> provide the best framework for organizing the mechanistic knowledge gained in this area. Proton transfer and Lewis acid catalysis form a huge body of data without organized counterparts on the electron side; why not accept to symmetrically balance this body by electron-transfer catalysis? The role of the proton as a small activating particle is now well-established. Very probably, within the beautiful isolobal approach,<sup>111</sup> much the same could be done on the electron side. W. Alder independently advocated such a symmetrical role for the proton and the electron.<sup>112</sup> In view of the growing importance of these processes in organometallic chemistry, this type of catalysis could enrich the scope of homogeneous catalysis induced by transition-metal complexes.<sup>113</sup>

The fact that this class of reactions is so general makes even more critical the still unanswered questions. We will finish by calling attention to them by a series of key words followed by references where relevant data can be found. On the fundamental side: electron-transfer-initiated reactions which should not be feasible according to Marcus theory;<sup>43,114,115</sup> for cases with concomitant formation of ionic and radical products,<sup>116</sup> step where the ionic-radical differentiation occurs;<sup>43,117</sup> origin of selectivity when ambident anions react;<sup>100</sup> homogeneous or heterogeneous origin of some selectivities;<sup>118</sup> role of ion pairing,<sup>119</sup> clustering,<sup>120</sup> and EDA complexes<sup>121</sup> in their processes; cooperativity or antagonism of proton- and electron-transfer catalysis;<sup>57i,122</sup> quantitative evaluation of every elementary step involved in the overall mechanism.<sup>101a</sup> On the practical side: best ex-

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(117) Harmony, J. In *Methods in Free Radical Chemistry*; Huyser, E., Ed.; Marcel Dekker: New York, 1974; Vol. 5, p 101.

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perimental conditions (photochemical, electrochemical, thermal, photosensitization)<sup>91,106</sup> to exploit a given reaction in this class; design of reactions using matrices of activation,<sup>91</sup> approximative correspondence principles,<sup>91</sup> tables of activation,<sup>57e</sup> application of these processes to reach new structures, activate inert substrates,

or obtain improved selectivities.

*I acknowledge with gratitude the contributions of my co-workers, whose names appear in the individual literature citations. The work described here has been supported by a joint grant from the CNRS-Royal Society, a NATO grant, and the CNRS.*

## Phospholipids and Proteins in Biological Membranes. <sup>2</sup>H NMR as a Method To Study Structure, Dynamics, and Interactions

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Cell membranes are very delicate structures, their average thickness measuring only 5–15 nm. They are invisible in the conventional light microscope but can easily be detected with the electron microscope.<sup>1</sup> Not only the whole cell but also the various organelles within the cell such as the nucleus, the mitochondria, the endoplasmic reticulum, etc., are surrounded by membranes of similar thickness.

The chemical composition of these thin separating walls is extremely complex, comprising a multitude of chemically quite different species. The main membrane constituents are lipids and proteins to which carbohydrates may be affixed covalently.<sup>2</sup> Each of these major building blocks is further divided into numerous chemical subgroups. The functional purpose of this chemical variability is, however, poorly understood.

The molecular packing of proteins and lipids in biological membranes follows a common pattern.<sup>3</sup> The basic structure is a continuous bilayer composed of phospholipids (and other amphiphatic molecules such as cholesterol) with their hydrocarbon chains sequestered toward the bilayer center and their hydrophilic polar groups exposed to the aqueous solution. Lipids are practically insoluble in water, and even though a pure lipid bilayer has a thickness of only 4–5 nm, it provides a sufficiently impermeable separating wall between two aqueous compartments, not so much for water but for charged solutes such as metal ions or macromolecules. The membrane proteins are found partly as insertions in the lipid bilayer, traversing the hydrophobic core of the bilayer, or as surface cover on both sides. The active functional properties of cell

membranes such as substrate transport, signal recognition, and cell–cell interaction are all thought to be mediated by the structurally complex and highly specialized membrane proteins.

The chemical structure of major lipid classes is quite simple, but as yet no unique functional role can be associated with a specific lipid. In a few cases (e.g., phosphatidylinositol) cofactor type of interactions have been postulated between lipids and membrane-bound proteins,<sup>4</sup> but for the most part, lipids appear to act collectively by modulating and amplifying the physicochemical properties of biomembranes or membrane domains.

Studies on simple membranes, composed of one or two types of lipids, have suggested several physical mechanisms by which lipids could influence membrane-associated protein activity. Firstly, the most obvious function of lipids is to act as a “grease” for the protein machinery, providing a fluidlike, two-dimensional solvent.<sup>5</sup> Different lipid species perform this role with varying efficacy. Secondly, depending on the chemical structure and the physical state of the fatty acyl chains, the membrane thickness will vary. A mismatch between the hydrophobic regions of the lipid matrix and the trans-membrane proteins could induce inhomogeneities in the lateral packing, leading to phase segregation and protein–protein association.<sup>6</sup> Thirdly, and perhaps most important, lipids could exert regulatory functions via the membrane surface potential<sup>7</sup> and via their ion binding properties.<sup>8</sup> These two parameters are mainly determined by the lipid polar

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