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ELECTROLYSIS AS A TYPE OF CATALYSIS: THE SAME MECHANISM, GENERAL LAWS AND THE SINGLE NATURE OF CATALYSIS AND ELECTROLYSIS

Abstract. *Electrolysis throughout its history has not been studied for the relationship between the nature of electrolysis and the nature of catalysis. The article makes a generalization of catalysis and electrolysis and reveals common features for these two fundamental processes. The concept of "electron as a catalyst" substantiates that electrolysis is a type of catalysis. The catalysts in electrolysis are electrons. A comparison of the mechanisms of electrolysis and catalysis is made. The mechanisms of electrolysis and catalysis are the same type of mirror-symmetric donor-acceptor mechanisms. In these mechanisms, the transfer of electric charges is realized. Electrolysis, as a catalytic process, has characteristics that are inherent to catalysis. These characteristics are the law of rate of electrolysis, the TOF of electrolysis, and the TON of electrolysis. Catalysis and electrolysis share common laws and a common genesis of laws. Faraday's law of electrolysis follows directly from the universal law of catalysis. Confirmation of the common nature of catalysis and electrolysis has been obtained. Electrolysis, as a type of catalysis, creates prerequisites for the creation of a general theory of catalysis and electrolysis.*

Keywords: *electrolysis, Faraday's law, "electron as a catalyst" concept, oxidation degree concept, relay donor-acceptor mechanism of catalysis and electrolysis, laws of catalysis and electrolysis, universal law of catalysis, new paradigm of catalysis.*

1. Introduction

It was shown in [1] that not only the laws of heterogeneous, homogeneous, and field catalysis, but also Faraday's law of electrolysis directly follow from the general law of catalysis rate. This is an unexpected result, since electrolysis does not belong to the class of catalytic reactions. Electrolysis, in its classical version, is considered an independent physical-chemical process. The reduction of the law of catalysis to Faraday's law of electrolysis forces a special study of electrolysis and catalysis for common features. The reduction of the laws may be evidence that catalysis and electrolysis belong to the same class of chemical-physical phenomena and have a common nature. This is also indicated by the fact that the main participants in electrolysis and catalysis are fundamental particles - electrons.

2. Electrolysis as a catalytic process that is catalyzed by electrons

The emergence of the concept of *"electron as a catalyst"* in the science of catalysis [2 - 13]. allows us to consider Faraday's electrolysis as a catalytic process that is catalyzed by electrons. Electrolysis produces simple substances from complex substances. Electrolysis can be viewed as a symmetrical catalytic process with respect to catalytic reactions of synthesis of complex substances from simple ones (Fig. 1).

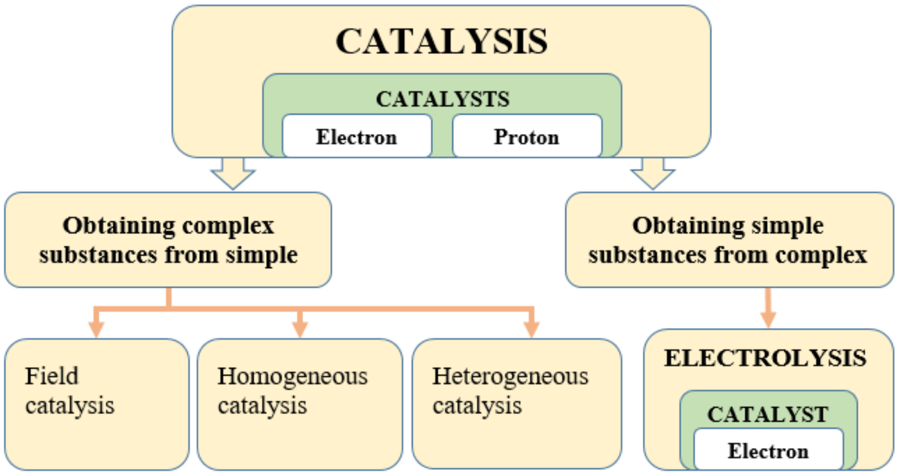

Fig. 1. Electrolysis as a symmetric process and a type of catalysis.

Electrolysis is considered an independent physical and chemical process. Electrolysis has not been studied for its general characteristics and its connection with catalysis. At the same time, it is known that Faraday studied the catalytic reaction involving platinum even before the discovery of catalysis. In 1834, Michael Faraday published a paper on catalysis [14], which outlined the mechanism of catalysis involving a platinum catalyst. This article was a profound study in the field of catalysis. It outlined the first theory of catalysis. It gave the rationale for the mechanism of catalytic reaction. In 1833, Faraday discovered electrolysis and worked on the mathematical formulation of the laws of electrolysis. During these years, both electrolysis and catalysis were subjects of Faraday's research. The law of electrolysis was discovered almost immediately following the discovery of electrolysis. Catalysis remains almost 200 years without a law of catalysis. Faraday's laws of electrolysis enriched science, but Faraday's theory of catalysis as outlined in the article was not accepted by his contemporaries. Faraday's article on catalysis (1834), for some reason, was not mentioned in Berzellius' 1835 report [15]. Clearly, the science of catalysis has lost much from underestimating Faraday's contribution to catalysis. The identification of common features in electrolysis and catalysis and the unification of these two phenomena into a single class of phenomena could be a stimulus for the development of the science of catalysis. Electrolysis as a type of catalysis and Faraday's laws of electrolysis can contribute to the science of catalysis. The purpose of this article is to reveal the profound connection between electrolysis and catalysis and to confirm the unified nature of electrolysis and catalysis.

3. Symmetry in the mechanisms of catalysis and electrolysis

A common feature in catalytic reactions and in electrolysis is the change in the charge state (oxidation degree) of the reaction participants under the action of the fundamental catalyst (electron). We took this common feature as the basis for developing models of catalysis and electrolysis mechanisms [16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28].

A simplified scheme of a catalytic reaction can be represented as follows:

$$A + B \longrightarrow A^{(-)} + B^{(+)} \longrightarrow AB$$

A simplified electrolysis scheme can be represented as:

$$AB \longrightarrow A^{(-)} + B^{(+)} \longrightarrow A + B$$

Fig. 2 shows schematics of heterogeneous catalysis and electrolysis mechanisms for comparison. Catalysis and electrolysis are symmetric processes in which mirror symmetry can be seen.

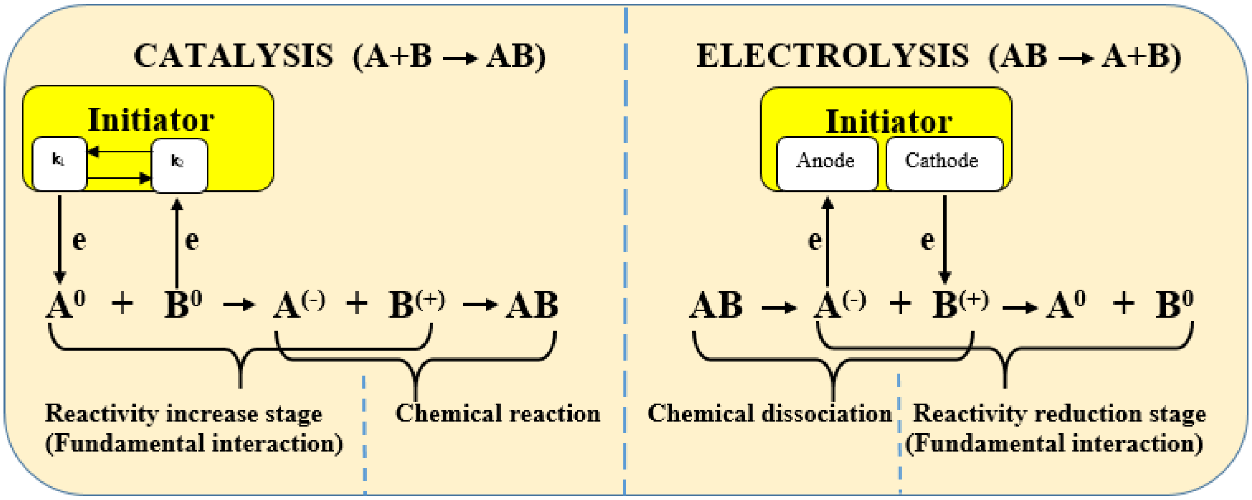

Fig. 2. Mirror symmetry in the mechanisms of heterogeneous catalysis and electrolysis.

In the scheme of catalysis: *A^0, B^0 - reagents; $A^{(-)}$ - reagent A in changed charge state; $B^{(+)}$ - reagent B in changed charge state; AB - reaction product; k_1 - initial oxidation degree of initiator; k_2 - final oxidation degree of initiator; e - electrons.*

In the diagram of electrolysis: *AB - initial substance; $A^{(-)}$ - product A in the changed charge state; $B^{(+)}$ - product B in the changed charge state; A^0, B^0 - products of electrolysis; e - electrons.*

Mirror symmetry in the mechanisms of heterogeneous catalysis and electrolysis manifests itself as follows. The donor function of electron transfer in catalysis corresponds to the acceptor function in electrolysis. For catalysis, the fundamental interaction stage precedes the chemical stage. For electrolysis, the fundamental interaction stage is realized after chemical dissociation. Electron transfer in catalysis leads to the formation of electrically charged particles from neutral ones. The transfer of electrons in electrolysis leads to the formation of neutral particles from electrically charged particles. Neutral particles A^0 and B^0 are the starting substances in catalysis. Neutral particles A^0 and B^0 in electrolysis are the end products. The directions of electron transfer in the diagrams of catalysis and electrolysis mechanisms are also mirror-symmetric.

4. The relay donor-acceptor mechanism of electrolysis

By analogy with the mechanism of catalysis [16, 17, 18], the elementary process of electrolysis can be represented by a scheme of the relay donor-acceptor mechanism. The scheme of the elementary electrolysis process mechanism is shown in Fig. 3.

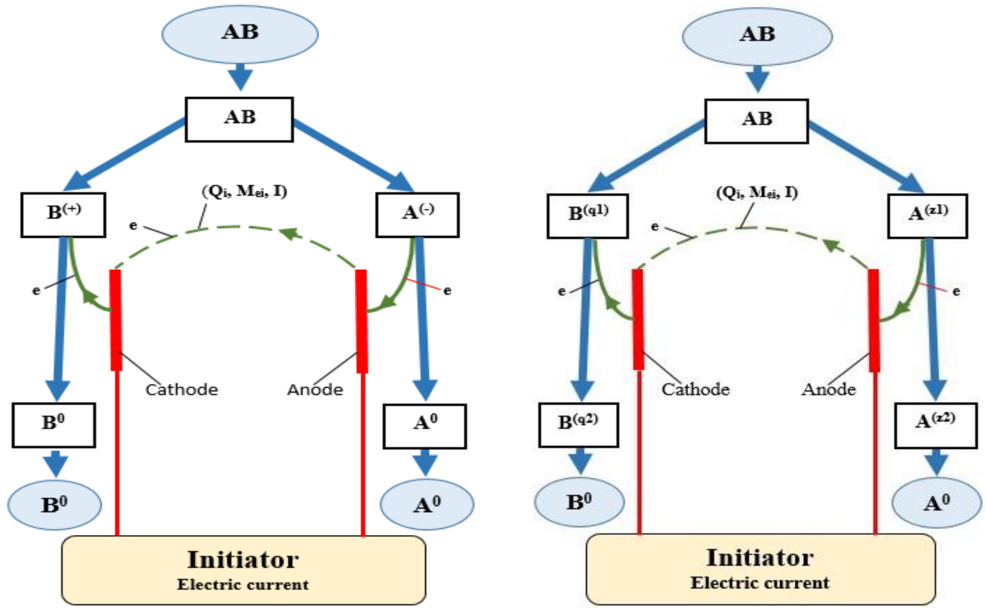

Fig. 3. Two equivalent diagrams of the relay donor-acceptor mechanism of electrolysis. *AB - initial substance;* $A^{(-)}$ *- product A in altered charge state;* $B^{(+)}$ *- product B in altered charge state;* A^0*,* B^0 *- electrolysis products;* $A^{(z1)}$*- product A in initial charge state;* $B^{(q1)}$ *- product B in initial charge state;* $A^{(z2)}$*- product A in final charge state;* $B^{(q2)}$ *- product B in the final charge state;* q_1*, initial degree of oxidation of products;* q_2*, final degree of oxidation of products; e - electrons;* Q_i *- electric charge; I - electric current; Mei - number of electrons participating in the elementary stage of electrolysis.*

Fig. 4 shows schemes of relay donor-acceptor mechanisms of heterogeneous catalysis and electrolysis. The catalysis mechanism involves the transfer of electrons between reagents. The initiator in catalysis acts as an intermediary in the relay transfer of electrons between reagents. In the mechanism of electrolysis, electrons are transferred between the products of chemical dissociation $A^{(-)}$ and $B^{(+)}$. The initiator (current source) in electrolysis mediates the transfer of electrons between the products of chemical dissociation $A^{(-)}$ and $B^{(+)}$

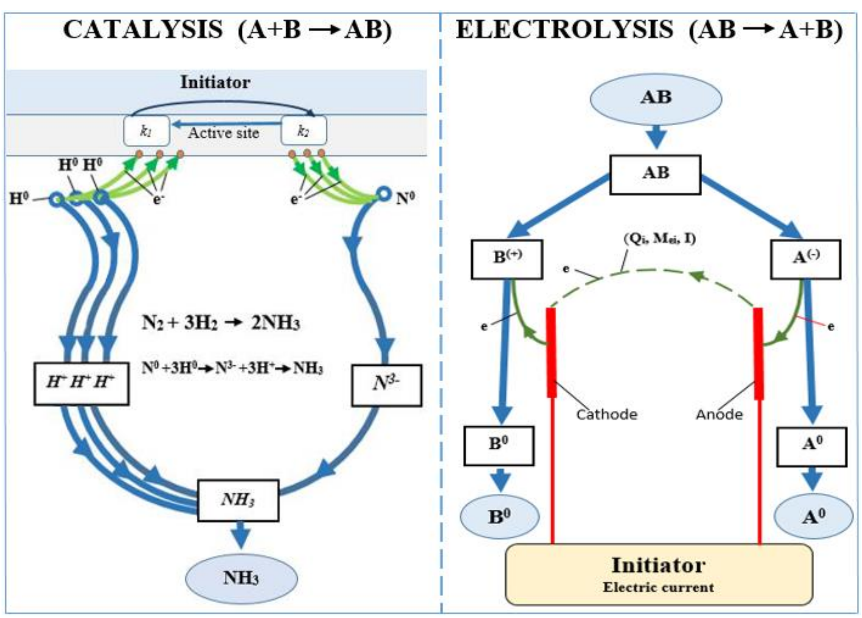

Fig. 4. Mirror symmetry and T-symmetry in relay donor-acceptor mechanisms of heterogeneous catalysis and electrolysis.

In the scheme of heterogeneous catalysis: *H^0- hydrogen atom in initial charge state; N^0- nitrogen atom in initial charge state; H^+- hydrogen atom in final charge state; N^{3-} nitrogen atom in final charge state; k_1- initial oxidation degree of the active initiator site; k_2- final oxidation degree of the active initiator site; e- - electrons; NH_3 - reaction product.*

In the scheme of electrolysis: *AB - initial substance; $A^{(-)}$ - product A in the changed charge state; $B^{(+)}$ - product B in the changed charge state; A^0, B^0 - electrolysis products; Q_i - electric charge; I - electric current; M_{ei} - number of electrons involved in the elementary stage of electrolysis.*

In the mechanisms of heterogeneous catalysis and electrolysis (Fig. 4) mirror symmetry is clearly expressed. We can speak of P-invariance of the relay donor-acceptor mechanisms of heterogeneous catalysis and electrolysis. In the sequence of catalysis and electrolysis stages, symmetry with respect to the direction of the processes is also pronounced. It is possible to speak about T-invariance of the relay donor-acceptor mechanisms of heterogeneous catalysis and electrolysis. Thus, the profound connection between the phenomena of electrolysis and catalysis is vividly manifested in the mirror-symmetric mechanisms of electrolysis and catalysis.

The symmetry in the mechanisms of catalysis and electrolysis indicates that there should be a single mathematical model for these two symmetric processes. Both symmetrical processes can be represented by one general equation. In particular, this applies to the laws of catalysis and the law of electrolysis. Based on the symmetry of the mechanisms of catalysis and electrolysis, the laws of catalysis and electrolysis can be represented by one general mathematical equation. Below is such a general mathematical equation for catalysis and electrolysis.

5. The concept of intermediate states instead of the concept of intermediate compounds

The appearance of the "*electron as a catalyst*" concept [2 - 13] and the assignment of fields to catalysts [29 - 43] force a radical revision of the generally accepted mechanism of catalysis. The generally accepted mechanism of catalysis is based on the formation of intermediate compounds of the catalyst with the reactants. The concept of intermediate compounds is not suitable for explaining the mechanism of field catalysis and the mechanism of catalysis by electrons. Instead of the concept of intermediate compounds, the concept of intermediate states has been proposed [16 - 28]. This is due to the special character of the interaction of the fundamental catalyst (electron) and the electric field with chemical substances. The electron as a catalyst does not form a new chemical substance in interaction with the reaction participants. It changes their charge state. The electric field also does not form a new chemical substance when interacting with the reaction participants. It leads to the appearance of charge-conjugate reaction participants. Instead of a catalytic cycle involving intermediate chemical compounds, catalytic charge-conjugate state cycles are implemented in the relay donor-acceptor mechanisms of catalysis and electrolysis. These cycles occur at the stage of the fundamental interaction of the participants in catalysis and electrolysis. In catalysis, the charge state cycle precedes the chemical reaction of modified reactants. In electrolysis, the cycle of charge states is realized after the stage of chemical dissociation. Intermediate states for reagents A and B in the catalytic reaction are their states in the modified oxidation degree $A^{(z2)}$ and $B^{(q2)}$ (Fig. 2, Fig. 4). Intermediate states for products of electrolysis A and B are also their states in the changed degree of oxidation $A^{(z2)}$ and $B^{(q2)}$ (Fig. 2, Fig. 3, Fig. 4).

6. Catalytic equations for electrolysis

To clarify the deep connection between the phenomena of electrolysis and catalysis, let us present Faraday's law in a modified form:

$$n_F = \frac{I \bullet t}{F \bullet q_1} = \frac{e \bullet M_e}{F \bullet q_1} \qquad (1)$$

where: n_F - quantity of substance (mol) in electrolysis; F - Faraday's constant; e - charge of electron; Me - number of electrons transferred to the product during electrolysis; I - value of electric current; q_1 - oxidation degree of the product in the initial substance; t - time.

Since electrons are the main active factor and the main participant in electrolysis, the charge of the electron *e* and the number of electrons M_e are introduced into the equation of the electrolysis law. As a result, Faraday's law of electrolysis (1) is presented in two equivalent forms. Faraday's law of electrolysis, presented in "electronic" form, allows us to reveal its connection with the laws of catalysis.

To reveal the connection between the law of electrolysis and the laws of catalysis, let us obtain from Faraday's law additional equations that characterize electrolysis as a catalytic process. To do this, we will use the characteristics accepted in catalysis (catalysis rate, TOF and TON). Let us apply these characteristics to electrolysis. For electrolysis, such catalytic equations are the rate law vF of electrolysis, TOF_F, and TON_F for electrolysis.

The vF rate law for electrolysis has the form:

$$v_F = \frac{I}{F \bullet q_1} = \frac{e \bullet M_e}{F \bullet t \bullet q_1}$$

TOF_F for electrolysis has the form:

$$TOF_F = \frac{I}{e \bullet q_1} = \frac{M_e}{t \bullet q_1}$$

TON_F for electrolysis has the form:

$$TON_F = \frac{I \bullet t}{e \bullet q_1} = \frac{M_e}{q_1}$$

The resulting electrolysis equations, which we will call "catalytic electrolysis equations" (Fig. 5), are obtained. These equations are presented in two equivalent views. A peculiarity of the catalytic equations of electrolysis is that the parameters in them are quantities that refer to the electron. These are the charge of the electron *(e)*, the number of electrons *(M_e)*, and Faraday's constant *(F)*.

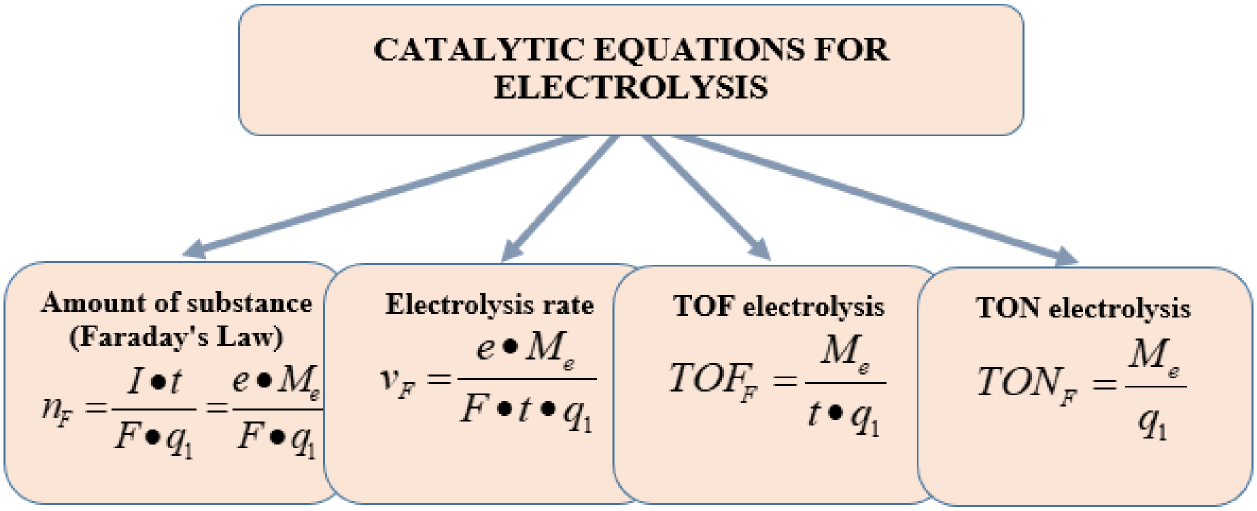

Fig. 5. Catalytic equations for electrolysis.

Catalytic equations for electrolysis are presented as a functional relationship of quantities. These quantities are the characteristics of the electrolysis participants. The participants of electrolysis are electrons, anode and cathode of current source (initiator), products A and B of electrolysis (Fig. 6). Parameters in catalytic equations of electrolysis are characteristics of participants. From the mechanism of electrolysis (Fig. 2, Fig. 3) it follows that the characteristics of initiator are the value of electric current I or the number of electrons M_e. The characteristics of catalyst-electron are the fundamental constants *(e, F)*. Characteristics of electrolysis products are their oxidation degrees in the initial substance and in the final stage (z_1, z_2, q_1, q_2).

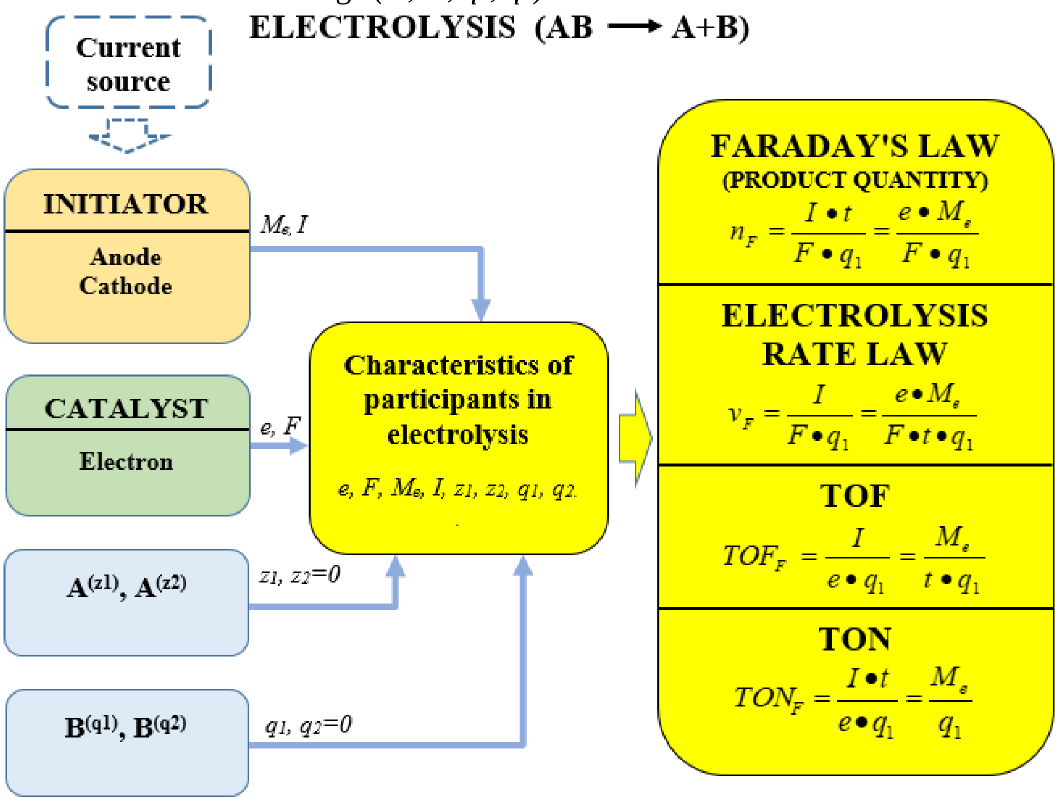

Fig. 6. From the characteristics of the electrolysis participants to the catalytic equations of electrolysis.

Faraday's law, the law of the rate of electrolysis, the TOF of electrolysis, and the TON of electrolysis follow directly from the mechanism of electrolysis (Fig. 7).

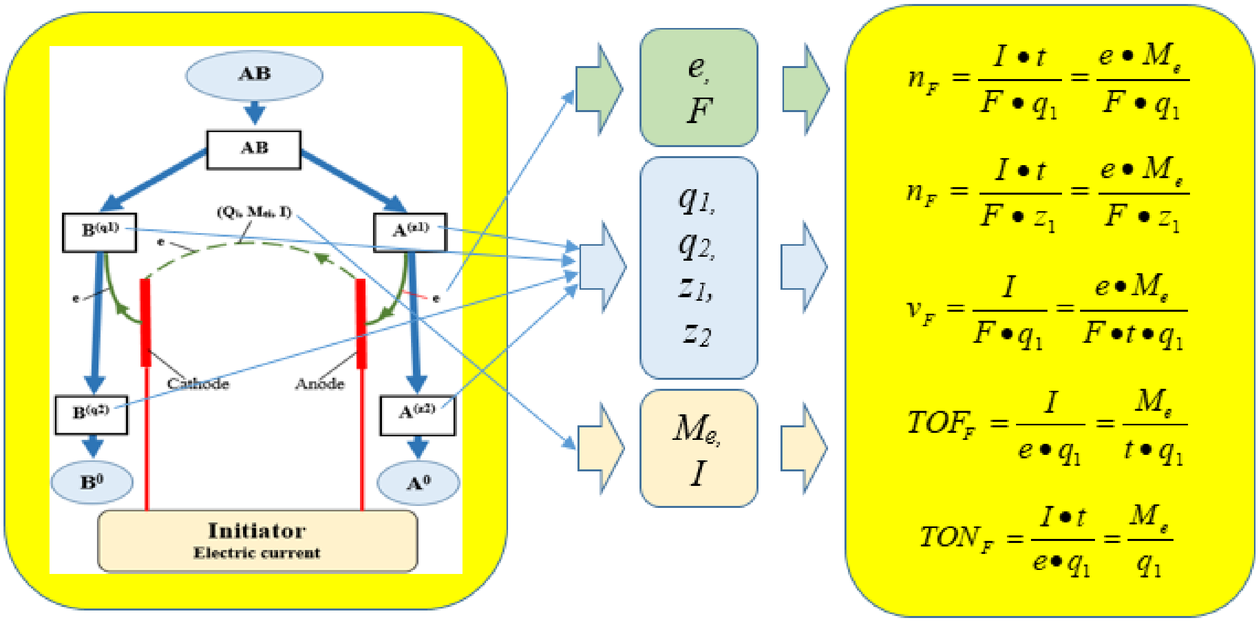

Fig. 7. Origin of the law of electrolysis and catalytic equations of electrolysis from the relay donor-acceptor mechanism of electrolysis.

7. General laws and equations for catalysis and electrolysis

The laws of catalysis are derived and generalized in [1, 16 - 28]. The above are catalytic equations for electrolysis. It is of interest to find out what connection exists between the laws of catalysis and the catalytic equations of electrolysis. The concept of *"electron as a catalyst"* gives the role of the catalyst to the electron. Therefore, we will present the generalized laws and equations of catalysis using the electron charge *(e)* and the number of electrons *(M_e).*

The generalized equation for the amount of product of catalysis reactions using the characteristics related to the electron has the form [1, 18]:

$$n_{cat} = \frac{e \bullet \sum_{i=1}^{m} M_{ei}}{F \bullet m_2 \bullet |q_1 - q_2|}$$

where: n_{cat} is the amount of matter (mol); F is Faraday's constant; e is the electron charge; M_{ei} is the number of electrons (protons) transferred to the reactant in an elementary reaction of catalysis; m is the number of elementary reactions; q_1 is the oxidation degree of the reactant in the initial product; q_2 is the oxidation degree of the reactant in the final product; m_2 is the number of reactant atoms in the final product molecule.

From the general equation for the amount of the reaction product of catalysis follow the equations of heterogeneous, homogeneous, field catalysis, and Faraday's law of electrolysis [1, 18] (Fig. 8).

$$n_{cat} = \frac{e \bullet \sum_{i=1}^{m} M_{e\,i}}{F \bullet m_2 \bullet |q_1 - q_2|}$$

$$n_{He} = \frac{e \bullet n_a \bullet t \bullet |k_1 - k_2|}{F \bullet (\tau_D + \tau_A) \bullet m_2 \bullet |q_1 - q_2|} \qquad n_{Ho} = \frac{e \bullet n_a \bullet t}{F \bullet (\tau_D + \tau_A) \bullet m_2 \bullet |q_1 - q_2|}$$

$$n_{Fcat} = \frac{t \bullet e \bullet f_e \bullet E_{cat}}{F \bullet m_2 \bullet |q_1 - q_2| \bullet E_i} \qquad n_F = \frac{I \bullet t}{F \bullet q_1} = \frac{e \bullet M_e}{F \bullet q_1}$$

Fig. 8. Origin of Faraday's law of electrolysis and equations of heterogeneous, homogeneous, field catalysis from the generalized law of catalysis.

An important indirect evidence of the unified nature of catalysis and electrolysis is the inclusion of Faraday's constant in the laws of catalysis (Fig. 8). This fundamental constant is a physicochemical constant. It is a linking constant between physical and chemical quantities: the electron charge and Avogadro's number. It is known that the Faraday constant enters not only into the formula of Faraday's law of electrolysis, but also into the Nernst equation and the Goldmann equation. Now Faraday's constant has designated itself in catalysis. Moreover, the fundamental status of Faraday's constant indicates the fundamental status of both catalysis and electrolysis.

The generalized equation of the general law of catalysis rate has the form 1, 18]:

$$v_{cat} = \frac{e \bullet \sum_{i=1}^{m} M_{e\,i}}{F \bullet t \bullet m_2 \bullet |q_1 - q_2|}$$

From the general law of the rate of catalysis follow the rate laws of heterogeneous, homogeneous, field catalysis and the rate law of electrolysis (Fig. 9).

$$v_{cat} = \frac{e \bullet \sum_{i=1}^{m} M_{e\,i}}{F \bullet t \bullet m_2 \bullet |q_1 - q_2|}$$

$$v_{He} = \frac{e \bullet n_a \bullet |k_1 - k_2|}{F \bullet (\tau_D + \tau_A) \bullet m_2 \bullet |q_1 - q_2|} \qquad v_{Ho} = \frac{e \bullet n_a}{F \bullet (\tau_D + \tau_A) \bullet m_2 \bullet |q_1 - q_2|}$$

$$v_{Fcat} = \frac{e \bullet f_e \bullet E_{cat}}{F \bullet m_2 \bullet |q_1 - q_2| \bullet E_i} \qquad v_F = \frac{I}{F \bullet q_1} = \frac{e \bullet M_e}{F \bullet t \bullet q_1}$$

Fig. 9. Origin of the electrolysis rate law and rate laws for heterogeneous, homogeneous, and field catalysis from the generalized catalysis rate law.

The generalized equation of TOF catalysis has the form [1, 18, 23]:

$$TOF_{cat} = \frac{\sum_{i=1}^{m} M_{ei}}{n_a \bullet t \bullet m_2 \bullet |q_1 - q_2|}$$

From the generalized equation of TOF catalysis follow TOF heterogeneous, homogeneous, field catalysis and the equation for TOF_F electrolysis (Fig. 10).

$$TOF_{cat} = \frac{\sum_{i=1}^{m} M_{ei}}{n_a \bullet t \bullet m_2 \bullet |q_1 - q_2|}$$

$$TOF_{He} = \frac{|k_1 - k_2|}{(\tau_D + \tau_A) \bullet m_2 \bullet |q_1 - q_2|} \qquad TOF_{Ho} = \frac{1}{(\tau_D + \tau_A) \bullet m_2 \bullet |q_1 - q_2|}$$

$$TOF_{Fcat} = \frac{f_e \bullet E_{cat}}{m_2 \bullet |q_1 - q_2| \bullet E_i} \qquad TOF_F = \frac{I}{e \bullet q_1} = \frac{M_e}{t \bullet q_1}$$

Fig. 10. Origin of TOF_F electrolysis and TOF_{He} heterogeneous, TOF_{Ho} homogeneous, TOF_{Fcat} field catalysis from the generalized equation of TOF_{cat} catalysis.

The generalized equation of TON catalysis has the form [1, 18, 23]:

$$TON_{cat} = \frac{\sum_{i=1}^{m} M_{ei}}{n_a \bullet m_2 \bullet |q_1 - q_2|}$$

From the generalized equation of TON catalysis follow TON heterogeneous, homogeneous, field catalysis and the equation for TON_F electrolysis (Fig. 11).

$$TON_{cat} = \frac{\sum_{i=1}^{m} M_{ei}}{n_a \bullet m_2 \bullet |q_1 - q_2|}$$

$$TON_{He} = \frac{|k_1 - k_2| \bullet t}{(\tau_D + \tau_A) \bullet m_2 \bullet |q_1 - q_2|} \qquad TON_{Ho} = \frac{t}{(\tau_D + \tau_A) \bullet m_2 \bullet |q_1 - q_2|}$$

$$TON_{Fcat} = \frac{t \bullet f_e \bullet E_{cat}}{m_2 \bullet |q_1 - q_2| \bullet E_i} \qquad TON_F = \frac{I \bullet t}{e \bullet q_1} = \frac{M_e}{q_1}$$

Fig. 11. Origin of TON_F electrolysis and TON_{He} heterogeneous, TON_{Ho} homogeneous, TON_{Fcat} field catalysis from the generalized equation of TON_{cat} catalysis.

Thus, the profound connection between the phenomena of electrolysis and catalysis manifests itself both in mirror-symmetric mechanisms and in the unified laws of catalysis and electrolysis.

8. The unified nature of catalysis and electrolysis.

The unified nature of catalysis and electrolysis is confirmed by the following:

1. The catalyst in both catalysis and electrolysis is the electron.

2. In catalysis and electrolysis, single-type symmetric mechanisms of catalysis are realized (Fig. 12).

3. The common feature in the mechanisms of catalysis and electrolysis is the transfer of electric charges by electrons and the change in the reactivity of the process participants. 4.

4. Electrolysis and catalysis have the same laws and the same genesis of the laws.

5. The laws of heterogeneous, homogeneous, field catalysis and Faraday's law of electrolysis are derived from one universal law of catalysis (Fig. 13).

6. Additional evidence of the unified nature of catalysis and electrolysis is the inclusion of Faraday's constant in the laws of catalysis and electrolysis.

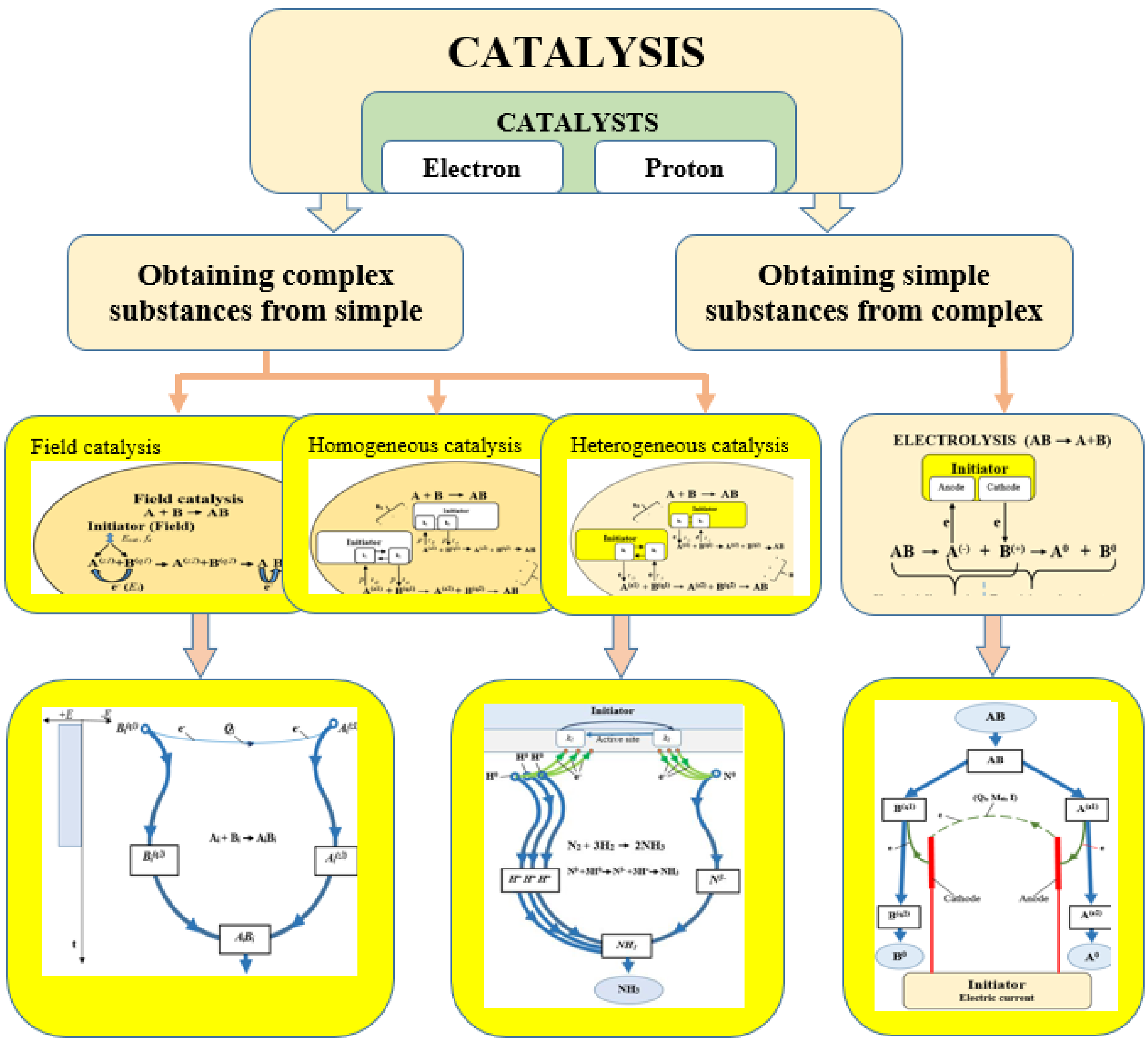

Fig. 12. In catalysis and in electrolysis, the same symmetrical mechanisms are implemented.

Fig. 13 shows the origin of the laws of heterogeneous, homogeneous, field catalysis from one universal law of catalysis. The laws and equations of electrolysis also derive from one universal law of catalysis.

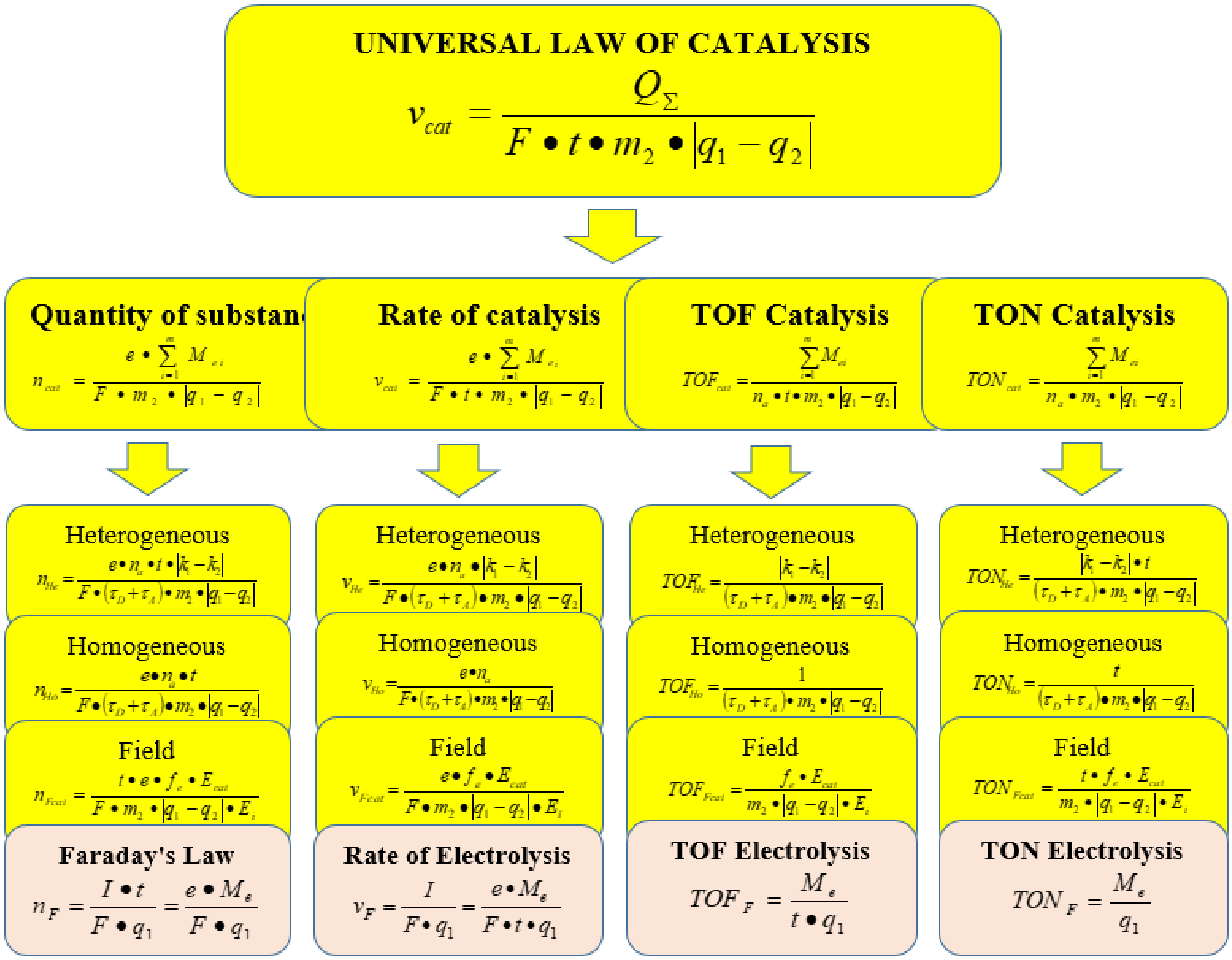

Fig. 13: The laws and equations of catalysis and electrolysis derive from one universal law of catalysis.

Thus, the unified nature of heterogeneous, homogeneous, field catalysis and electrolysis is confirmed. The laws and equations of heterogeneous, homogeneous, and field catalysis derive from one universal law of catalysis. From the same universal law of catalysis come Faraday's law of electrolysis, the law of the rate of electrolysis, and the equations of electrolysis.

9. Conclusion

The general laws and unified mechanism of catalysis and electrolysis allow us to consider electrolysis as a type of catalysis. It turns out that catalysis is a more widespread chemical-physical phenomenon than usually thought. Processes in which the reactivity of participants is changed under the action of electrons or protons should be classified as catalytic processes. The change in the reactivity of substances in catalytic reactions and in electrolysis occurs at the stage of the fundamental interaction of the process participants. The change in the reactivity of substances occurs under the action of fundamental particles - electrons and protons. These elementary particles are universal and fundamental catalysts. This applies both to catalytic processes of the formation of complex substances from simple ones and to catalytic processes of the formation of simple substances from complex ones.

More than 200 years have passed since the first catalytic reactions were discovered. However, catalysis has no general theory explaining the catalytic action of substances. There are many indications that catalysis is fundamental. However, it has no fundamental laws of catalysis. About 190 years have passed since the discovery of electrolysis and its laws. All this time, electrolysis has not been considered a type of catalysis. Attributing electrolysis and its laws to catalysis opens up new possibilities for the science of catalysis. In this respect, electrolysis, as a type of catalysis, becomes a good basis for the creation of a general theory of catalysis and electrolysis. The future unified theory of catalysis must unite not only different kinds of catalysis, but also include electrolysis and its laws.

10. Conclusions

1. Electrolysis is a type of catalysis.

2. Electrolysis, as a catalytic process, has characteristics that are relevant to catalysis. These characteristics are the law of rate of electrolysis, the TOF of electrolysis, and the TON of electrolysis.

3. The common nature of catalysis and electrolysis is confirmed by their similar mechanisms and the common genesis of the laws from one universal law of catalysis.

4. In both electrolysis and catalysis, a relay donor-acceptor mechanism is realized. The mechanism of electrolysis and the mechanism of catalysis are two mirror-symmetric mechanisms.

5. In mirror-symmetric donor-acceptor mechanisms of electrolysis and catalysis the transfer of electric charges is realized. This leads to a change in the reactivity of the reactants.

6. The relay donor-acceptor mechanism model is an ununiversal model of catalysis and electrolysis mechanisms.

7. Faraday's law of electrolysis, the equations of electrolysis, and the laws of heterogeneous, homogeneous, and field catalysis derive from one universal law of catalysis.

8. The catalytic equations of electrolysis are a good basis for a general theory of catalysis and electrolysis.

References

1. Volodymyr Kaplunenko, Mykola Kosinov. THE UNIVERSAL LAW OF CATALYSIS. July 2022. DOI: 10.13140/RG.2.2.12734.97607
2. Davis, D.; Vysotskiy, V.P.; Sajeev, Y.; Cederbaum, L.S. Electron Impact Catalytic Dissociation: Two-Bond Breaking by a Low-Energy Catalytic Electron. *Angew. Chem. Int. Ed.* 2011, *50*, 4119– 4122. https://doi.org/10.1002/ange.201005129
3. Davis, D.; Vysotskiy, V.P.; Sajeev, Y.; Cederbaum, L.S. A One-Step Four-Bond-Breaking Reaction Catalyzed by an Electron. Angew. Chem. Int. Ed. 2012, Volume124, Issue32, August 6, 2012. Pages 8127-8131. https://doi.org/10.1002/ange.201204162
4. Daly Davis, Y. Sajeev. COMMUNICATION: Low-energy-electron induced permanently reactive CO2 molecules. July 2014. Physical Chemistry Chemical Physics 16(33). DOI: 10.1039/C4CP02701A

5. Daly Davis, Y. Sajeev. COMMUNICATION: Low energy electron catalyst: Electronic origin of catalytic strategies. September 2016. Physical Chemistry Chemical Physics 18(40). DOI: 10.1039/C6CP05480C
6. Davis, D.; Kundu, S.; Prabhudesai, V.S.; Sajeev, Y.; Krishnakumar, E. Formation of CO_2 from formic acid through catalytic electron channel. J. Chem. Phys. 149, 064308 (2018); https://doi.org/10.1063/1.5032172
7. Studer, A., Curran, D. The electron is a catalyst. *Nature Chem* 6, 765–773 (2014). https://doi.org/10.1038/nchem.2031
8. Jun Xuan, Constantin G. Daniliuc, and Armido Studer . Construction of Polycyclic γ-Lactams and Related Heterocycles via Electron Catalysis. *Organic Letters* 2016, *18* (24) , 6372-6375. https://doi.org/10.1021/acs.orglett.6b03267
9. Shubhadip Mallick, Pan Xu, Ernst-Ulrich Würthwein, Armido Studer. Silyldefluorination of Fluoroarenes by Concerted Nucleophilic Aromatic Substitution. *Angewandte Chemie* **2019,** *131* (1) , 289-293. https://doi.org/10.1002/ange.201808646
10. Abhishek Dewanji, Christian Mück-Lichtenfeld, Armido Studer. Radical Hydrodeiodination of Aryl, Alkenyl, Alkynyl, and Alkyl Iodides with an Alcoholate as Organic Chain Reductant through Electron Catalysis. *Angewandte Chemie* 2016, *128* (23) , 6861-6864. https://doi.org/10.1002/ange.201601930
11. M. Lübbesmeyer, D. Leifert, H. Schäfer, A. Studer. Electrochemical initiation of electron-catalyzed phenanthridine synthesis by trifluoromethylation of isonitriles. *Chemical Communications* 2018, *54* (18) , 2240-2243. https://doi.org/10.1039/C7CC09302K
12. Dirk Leifert, Denis G. Artiukhin, Johannes Neugebauer, Anzhela Galstyan, Cristian Alejandro Strassert, Armido Studer. Radical perfluoroalkylation – easy access to 2-perfluoroalkylindol-3-imines via electron catalysis. *Chemical Communications* **2016,** *52* (35) , 5997-6000. https://doi.org/10.1039/C6CC02284G
13. Project Information. The Electron as a Catalyst. **https://cordis.europa.eu/project/id/692640**
14. Faraday, M., Experimental Researches in Electricity – Sixth Series. On the Power of Metals and other Solids to Induce the Combination of Gaseous Bodies, Phil. Trans., 124, 55-76, 1834. Faraday M. // Phil. Trans. Roy. Soc. 1834. 124. P. 55.
15. Lunin V.V., Romanovsky B.V. CATALYSIS: EXPERIENCE OF HISTORICAL AND METHODOLOGICAL ANALYSIS. Vestn. Moscow Univ., Ser. 2. Chemistry. 1999. V. 40, No. 5.
16. Volodymyr Kaplunenko, Mykola Kosinov. THE CONCEPT OF ELECTRON AS A CATALYST IS THE KEY TO UNLOCKING THE SECRETS OF CATALYSIS. January 2023. DOI: 10.13140/RG.2.2.22445.97760
17. Volodymyr Kaplunenko, Mykola Kosinov. FROM THE "ELECTRON AS A CATALYST" CONCEPT TO A NEW PARADIGM OF CATALYSIS. December 2022, DOI: 10.13140/RG.2.2.29232.64008
18. Volodymyr Kaplunenko, Mykola Kosinov. FROM THE "ELECTRON AS A CATALYST" CONCEPT TO THE LAWS OF CATALYSIS. DOI: 10.13140/RG.2.2.16467.86567
19. Volodymyr Kaplunenko, Mykola Kosinov. (2022). From the concept of "Electron as a catalyst" to a single mechanism of catalytic reactions. *Scientific Collection «InterConf+»*, 28(137), 339–357. https://doi.org/10.51582/interconf.19-20.12.2022.036

20. Volodymyr Kaplunenko, Mykola Kosinov. CATALYSIS: A FUNDAMENTAL PHENOMENON AT THE INTERFACE BETWEEN SCIENCES AND DISCIPLINESS. October 2022. DOI: 10.13140/RG.2.2.18460.97920
21. Kosinov M. V., Kaplunenko V. G. Method for accelerating heterogeneous catalysis above the Sabatier maximum. Patent UA 150017, (2021).
22. Kosinov M. V., Kaplunenko V.G. Method for determining the activity of the catalyst. Patent UA № 151629. 25.08.2022.
23. Kaplunenko V. G. Kosinov M. V. (2021). TOF AND TON EVOLUTION IN HETEROGENEOUS CATALYSIS. InterConf, (93), 417-450. https://doi.org/10.51582/interconf.21-22.12.2021.046
24. Kaplunenko, V., & Kosinov, M. (2022). LAWS OF HETEROGENEOUS CATALYSIS. *InterConf*, (105), 376-398. https://doi.org/10.51582/interconf.19-20.04.2022.037
25. Kaplunenko, V., & Kosinov, M. (2021). DONOR-ACCEPTOR THEORY OF HETEROGENEOUS CATALYSIS. InterConf, (71), 316-331. https://doi.org/10.51582/interconf.19-20.08.2021.031
26. Kaplunenko, V., & Kosinov, M. (2022). LAWS OF HOMOGENEOUS CATALYSIS. https://www.researchgate.net/publication/361587838_LAWS_OF_HOMOGENEOUS_CATALYSIS
27. Volodymyr Kaplunenko, Mykola Kosinov. Electric field - induced catalysis. Laws of field catalysis. DOI: 10.51582/interconf.19-20.10.2022.037
28. Volodymyr Kaplunenko, Mykola Kosinov. Changing the paradigm of catalysis: breaking stereotypes. November 2022. DOI: 10.51582/interconf.19-20.11.2022.027
29. Andrés, J. L.; Lledós, A.; Duran, M.; Bertrán, J. Electric Fields Acting as Catalysts in Chemical Reactions. An ab Initio Study of the Walden Inversion Reaction. Chem. Phys. Lett. 1988, 153, 82− 86. https://doi.org/10.1016/0009-2614(88)80136-2
30. Carbonell, E.; Duran, M.; Lledós, A.; Bertrán, J. Catalysis of Friedel-Crafts Reactions by Electric Fields. J. Phys. Chem. A. 1991, 95, 179−183. https://doi.org/10.1021/j100154a036
31. Giovanni Camera-Roda, Carlos A.Martin. Design of photocatalytic reactors made easy by considering the photons as immaterial reactants. Solar Energy. Volume 79, Issue 4, October 2005, Pages 343-352. https://doi.org/10.1016/j.solener.2005.02.025
32. Janhavi Dere Effect of an external electric field on the oxidation of CO to CO2 on a nickel oxide catalyst December 1974 Journal of Catalysis 35(3):369-375 DOI: 10.1016/0021-9517(74)90219-X
33. Hidefumi Hiura, Atef Shalabney, Jino George. Vacuum-Field Catalysis: Accelerated Reactions by Vibrational Ultra Strong Coupling. 26.05.2021. DOI: 10.26434/chemrxiv.7234721.v4
34. Hidefumi Hiura and Atef Shalabney. A Reaction Kinetic Model for Vacuum-Field Catalysis Based on Vibrational LightMatter Coupling. 07.08.2019. DOI: 10.26434/chemrxiv.9275777
35. Stoukides, M.; Vayenas, C. G. The Effect of Electrochemical Oxygen Pumping on the Rate and Selectivity of Ethylene Oxidation on Polycrystalline Silver. *J. Catal.* 1981, *70* (1), 137– 146, DOI: 10.1016/0021-9517(81)90323-7
36. Thejas S. Wesley, Yuriy Román-Leshkov and Yogesh Surendranath. Spontaneous Electric Fields Play a Key Role in Thermochemical Catalysis at Metal−Liquid Interfaces. *ACS Cent. Sci.* 2021, 7, 6, 1045–1055. Publication Date:June 2, 2021.

https://doi.org/10.1021/acscentsci.1c00293)
37. Vayenas, C. G.; Bebelis, S.; Ladas, S. Dependence of Catalytic Rates on Catalyst Work Function. *Nature* 1990, *343*, 625– 627, DOI: 10.1038/343625a0
38. Warburton, R. E.; Hutchison, P.; Jackson, M. N.; Pegis, M. L.; Surendranath, Y.; Hammes-Schiffer, S. Interfacial Field-Driven Proton-Coupled Electron Transfer at Graphite-Conjugated Organic Acids. *J. Am. Chem. Soc.* 2020, *142* (49), 20855– 20864, DOI: 10.1021/jacs.0c10632
39. Shaik, S.; Danovich, D.; Joy, J.; Wang, Z.; Stuyver, T. Electric-Field Mediated Chemistry: Uncovering and Exploiting the Potential of (Oriented) Electric Fields to Exert Chemical Catalysis and Reaction Control. *J. Am. Chem. Soc.* 2020, *142* (29), 12551– 12562, DOI: 10.1021/jacs.0c05128
40. Bockris, J. O.; Reddy, A.; Gamboa-Aldeco, M. *Modern Electrochemistry 2A: Fundamentals of Electrodics*, 2nd ed.; Springer: Boston, MA, 2000.
41. Neophytides, S. G.; Tsiplakides, D.; Stonehart, P.; Jaksic, M. M.; Vayenas, C. G. Electrochemical Enhancement of a Catalytic Reaction in Aqueous Solution. *Nature* 1994, *370*, 45– 47, DOI: 10.1038/370045a0
42. Zang, Y., Zou, Q., Fu, T. *et al.* Directing isomerization reactions of cumulenes with electric fields. *Nat Commun* **10**, 4482 (2019). https://doi.org/10.1038/s41467-019-12487-w
43. Anirban Das, Gyandshwar Kumar Rao, Kasinath Ojha. Photoelectrochemical Generation of Fuels. (2022). ISBN: 9781003211761. DOI: 10.1201/9781003211761)