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THE UNIVERSAL LAW OF CATALYSIS

Abstract. *The general sign and general mechanism of catalytic reactions based on the transfer of electric charges to reagents has been revealed. This mechanism of catalysis is realized on the fundamental level - on the level of interaction of elementary particles (electrons and protons). The choice of this mechanism of catalysis made it possible to obtain the general law of catalysis and private laws for other types of catalysis. The main parameter in the equation of the generalized law of catalysis is the total electric charge obtained by the reactants. In catalysis, the donor-acceptor mechanism is realized, which leads to a change in the oxidation state of the reactants and to a decrease in the activation energy of the chemical reaction. The main active factor in the donor-acceptor mechanism of catalysis is the electrical charge that transfers the catalyst to the reactants. The electric charge is a quantitative characteristic in the formula for the universal law of catalysis. From the universal law of catalysis, the laws of heterogeneous, homogeneous, combined, field catalysis, and Faraday's law of electrolysis follow as private results.*

Keywords: *laws of catalysis, generalized law of catalysis, field - immaterial catalyst, donor-acceptor mechanism of catalysis, electric charge, oxidation states of reactants, electrolysis - special case of catalysis, Faraday's constant.*

1. Introduction

The practice of catalysis is struck by a great variety of catalytic reactions, which are difficult to generalize. Despite the advances made in the practice of catalysis, the scientific side of this physical and chemical phenomenon remains poorly understood. The nature of the catalytic action is currently only partially clear, and a quantitative theory has not been established. There is no equation that can describe the law of catalytic reaction rate [1 - 6]. A large number of types of catalysis need theoretical substantiation and generalization. In this article, we aim to obtain a single generalized law of catalysis, from which laws for different types of catalysis should follow as special cases.

2. Common acting factor in catalytic reactions

The successful selection of a catalyst and the conditions for a particular reaction is based on empirical selection. Therefore, the identification of the common active factor in catalysis is an urgent task. The multitude of types of catalysis and the variety of catalysts creates a false idea that the active factors of catalysis are the features of the chemical composition and the chemical structure of the catalyst. A universal active factor in catalysis has not yet been identified. The emergence of immaterial field catalysts in catalysis points to the presence of some common property in catalysts different in nature.

The ability of fields to act as immaterial catalysts [7 - 18] indicates that this common property of catalysts has nothing to do with the chemical composition and chemical structure of the catalysts. Both the field and the substance have this common property. The mechanism of field catalyst action cannot be explained by the formation of intermediate compounds between the catalyst-field and the reactants [19]. It was shown in [19-22] that such a common property of substance and field catalysts is their ability to change the oxidation state of the reactants. As a result, this leads to a decrease in the activation energy of the chemical reaction. The material objects that realize this ability of catalysts are two elementary particles: an electron and a proton [23, 24].

The common feature of the electron and proton is their identical electric charge ($e = 1.602\ 176\ 634 \times 10^{-19}$ C). The electric charges of the electron and proton claim to be universal acting factors in catalysis. They initiate and accelerate the chemical reaction. The electrical nature of catalysis is obvious. The mechanism that realizes the transfer of electric charges is the donor-acceptor mechanism of catalysis. This mechanism of catalysis is realized on the fundamental level - the level of interaction of elementary particles (electrons and protons).

3. Back to Berzelius - closer to the electrical mechanism of catalysis

The electrical mechanism of catalysis was pointed out by Berzelius long before the discovery of the electron and proton, already in the first years after the discovery of catalysis. Berzelius developed a theory of catalysis based on the catalytic force, noting that "the catalytic force must consist in some influence on the polarity of the atoms which it increases, decreases or changes so that in fact it is based on the excitation of electrical relations. These electrical relationships have so far eluded our research" [25, 26]. His teachings were not supported by his contemporaries. The results obtained in [19 - 24] show that Berzelius's phenomenological theory of catalysis and his catalytic power were not the scientist's mistakes. The material carriers of Berzelius's catalytic force were identified. These are the elementary particles - the electron and the proton. And the catalytic force appeared in the laws of catalysis as a force interaction of electric charges.

4. The donor-acceptor mechanism is the universal mechanism of catalysis

The role of electrons and protons as carriers of electric charges is crucial in catalytic reactions. The reaction of the form A + B = AB in the presence of a heterogeneous Cat catalyst can be represented by the scheme shown in Fig. 1.

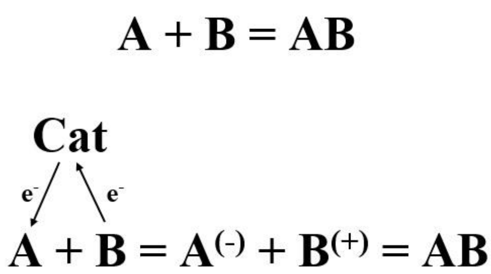

Fig. 1. Scheme of heterogeneous catalysis. A, B - reagents. AB - reaction product. $A^{(-)}$, $B^{(+)}$ - ionized reagents. Cat - heterogeneous catalyst. e^-- electron charge.

In heterogeneous catalysis, the catalyst acts as an electron donor and acceptor when interacting with reagents. The catalyst electrons allow the reaction activation energy to be reduced by changing the oxidation state of the reactants. The change in the zaradic state of the reactants is the main result of the donor-acceptor interaction. The catalyst itself remains unchanged and participates in the reaction with its electrons e^-.

The reaction of the form A+B = AB in the presence of a homogeneous Cat catalyst can be represented by the scheme shown in Fig. 2.

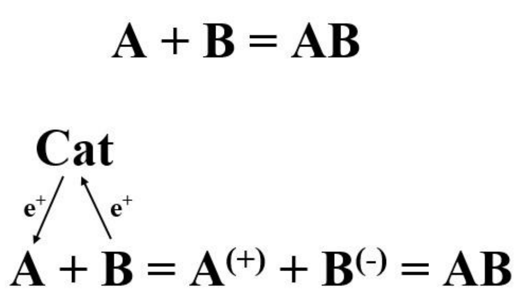

Fig. 2. Scheme of homogeneous catalysis. A, B - reagents. AB - reaction product. $A^{(-)}$, $B^{(+)}$ - ionized reagents. Cat - homogeneous catalyst. e^+ - proton charge.

The transfer of electric charges by e+ protons in homogeneous catalysis leads to a change in the oxidation state of the reactants. This causes ionization of the reactants and changes the reactivity of the substances, which leads to an acceleration of the chemical reaction. The catalyst itself remains unchanged and participates in the reaction with its protons.

The reaction of the form A+B = AB in the presence of the Cat(Field) field catalyst can be represented by the scheme shown in Fig. 3.

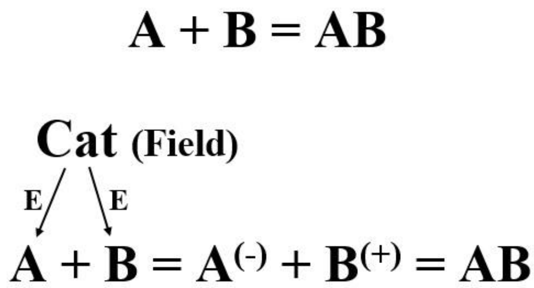

Fig. 3. Scheme of field catalysis. A, B - reagents. AB - reaction product. $A^{(-)}$, $B^{(+)}$ - ionized reagents. Cat(Field) - field catalyst. E - field energy.

Field catalysts participate in the reaction by the field energy E, which leads to the generation of electrons in the substance of the reactants. This causes ionization of the reactants. In this case, the role of an electron donor in a catalytic reaction is performed by one of the reactants, and the role of an electron acceptor is performed by the other reactant. This makes it possible to reduce the activation energy of the reaction by changing the oxidation state of the reactants. The catalyst (field) itself remains unchanged and participates in the reaction with its energy.

The reaction of the form A+B = AB in the presence of the combined catalyst Cat(1) + Cat(2) can be represented by the scheme shown in Fig. 4.

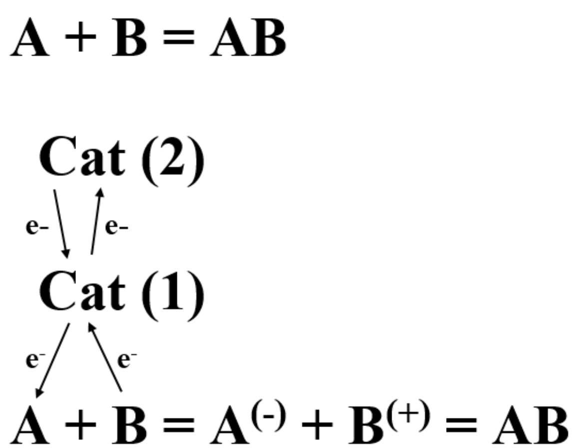

Fig. 4. Scheme of combined catalysis. A, B - reagents. AB - reaction product. $A^{(-)}$, $B^{(+)}$ - ionized reagents. Cat(1) + Cat(2) - combined catalyst. e- - electron charge.

The catalysts in the combined catalysis act as an electron donor and acceptor. The second catalyst enhances the action of the first catalyst. The first catalyst interacts directly with the reagents by implementing a donor-acceptor mechanism of catalysis. The second catalyst can be an electric current (electrocatalysis), an electric field (electrostatic catalysis), light (photocatalysis, daser catalysis), ionizing radiation (radiation catalysis), etc. Combined catalyst electrons allow the reaction activation energy to be reduced by changing the oxidation state of the reactants. At the same time, the catalysts themselves remain unchanged and participate in the reaction with e- electrons.

The model of donor-acceptor interaction of the catalyst and reactants was first proposed by Thomas Martin Lowry in 1925-1928. He formulated the idea of a proton-donor-acceptor mechanism as applied to homogeneous catalytic processes. According to Lowry, homogeneous catalysis is caused by the alternating interaction of a reactant molecule with a catalyst. The mechanism consists in the attachment by the reactant of a proton received from the donor catalyst and the subsequent transfer of protons to the catalyst-acceptor [27, 28].

The electronic donor-acceptor mechanism of heterogeneous catalysis has been extensively studied by Jia Min Jin. [29, 30]. According to Jia Min Jin, the donor-acceptor mechanism helps to explain many experimental results of heterogeneous catalysis, including catalysis and poisoning, the activity of various catalysts, and the choice of carrier material [29, 30].

The donor-acceptor mechanism was shown in [19 - 24] to claim the status of a universal mechanism of catalysis. The applicability limits of this mechanism go far beyond heterogeneous and homogeneous catalysis and extend to other types of catalysis. The donor-acceptor mechanism allowed the laws of heterogeneous, homogeneous, and field catalysis to be obtained [19, 21, 24]. The equations of these laws of catalysis include electric charge as a quantitative measure.

In this article, we will show that accepting the electrical nature of catalysis and the donor-acceptor mechanism of catalysis allows us to obtain a universal law of catalysis. From the generalized law of catalysis follow the laws of various kinds of catalysis and even Faraday's law of electrolysis.

5. The general law of catalysis for different types of catalysis

Different types of catalysis must obey the same general law. This is indicated by the electrical nature of different types of catalysis. This is indicated by the uniform transfer of electric charges by elementary particles in different types of catalysis. This is indicated by the universal nature of the donor-acceptor mechanism of catalysis.

In order to obtain a general law of catalysis, we will analyze and compare the rate law formulas obtained earlier in [19, 21, 24] for three types of catalysis: heterogeneous, homogeneous, and field catalysis.

$$v_{He} = \frac{e \bullet n_a \bullet |k_1 - k_2|}{F \bullet (\tau_D + \tau_A) \bullet m_1 \bullet |z_1 - z_2|} \qquad (1)$$

$$v_{Ho} = \frac{e \bullet n_a}{F \bullet (\tau_D + \tau_A) \bullet m_1 \bullet |z_1 - z_2|} \qquad (2)$$

$$v_{Fcat} = \frac{e \bullet f_e \bullet E_{cat}}{F \bullet m_1 \bullet |z_1 - z_2| \bullet E_i} \qquad (3)$$

where: v_{He} is the rate of heterogeneous catalysis (mol/s); v_{Ho} is the rate of homogeneous catalysis (mol/s); v_{Fcat} is the rate of field catalysis (mol/s); n_a – the number of active catalyst centers involved in the reaction; F - is Faraday's constant; e - is the electric charge of the electron; τ_D - is the donor half-loop of catalysis; τ_A - is the acceptor half-loop of catalysis; f_e - is the frequency of field influence on reagents; E_{cat} - field energy spent on catalysis during one cycle of catalysis (J); E_i - energy of ionization of reactants (J); k_1 - initial degree of oxidation of the catalyst; k_2 - final degree of oxidation of the catalyst; z_1 – degree of oxidation of the reactant in the initial product; z_2 – degree of oxidation of the reactant in the final product; m_1 - number of reactant atoms in the molecule of the final product; t - catalytic reaction time.

All three formulas (1), (2), (3) have a common feature. These formulas include combinations of values that specify the value of the electric charge. This is the electric charge transferred to the reactant and the electric charge received by the reactant.

In the law of heterogeneous catalysis (1) electric charge is represented by the following combination of values:

$$Q_\Sigma = \frac{e \bullet n_a \bullet |k_1 - k_2| \bullet t}{(\tau_D + \tau_A)} \qquad (4)$$

In the law of homogeneous catalysis (2) the electric charge is represented by the following combination of quantities:

$$Q_\Sigma = \frac{e \bullet n_a \bullet t}{(\tau_D + \tau_A)} \qquad (5)$$

In the law of field catalysis (3), the electric charge is represented by the following combination of quantities:

$$Q_\Sigma = \frac{e \bullet f_e \bullet E_{cat} \bullet t}{E_i} \qquad (6)$$

The general formula for the rate law of catalysis vcat and the general formula for calculating the yield of the catalysis reaction ncat will be presented as:

$$v_{cat} = \frac{Q_{\Sigma}}{F \bullet t \bullet m_1 \bullet |z_1 - z_2|} \qquad (7)$$

$$n_{cat} = \frac{Q_{\Sigma}}{F \bullet m_1 \bullet |z_1 - z_2|} \qquad (8)$$

We see that different types of catalysis obey a general law. Relations (7) and (8) are mathematical expressions of this general law of catalysis. The general law of catalysis applies not only to homogeneous, heterogeneous, and field catalysis. Below we will show its universal character. The scope of applicability of the general law of catalysis extends far beyond heterogeneous, homogeneous, and field catalysis to other types of catalysis.

Table 1 shows the generalized law of catalysis rate and catalysis reaction yield and their reduction to the partial laws of catalysis.

Table 1

Name	**Formulas for the laws of catalysis**	**Note**
Generalized law of the rate of catalysis and the yield of the catalytic reaction	$v_{cat} = \frac{Q_{\Sigma}}{F \bullet t \bullet m_1 \bullet \lvert z_1 - z_2 \rvert}$ **;** $n_{cat} = \frac{Q_{\Sigma}}{F \bullet m_1 \bullet \lvert z_1 - z_2 \rvert}$	Q_{Σ} - electrical charge
Reduction of the law of catalysis rate to the law of heterogeneous catalysis	$v_{He} = \frac{Q_{\Sigma}}{F \bullet t \bullet m_1 \bullet \lvert z_1 - z_2 \rvert} = \frac{e \bullet n_a \bullet \lvert k_1 - k_2 \rvert}{F \bullet (\tau_D + \tau_A) \bullet m_1 \bullet \lvert z_1 - z_2 \rvert}$	$Q_{\Sigma} = \frac{e \bullet n_a \bullet \lvert k_1 - k_2 \rvert \bullet t}{(\tau_D + \tau_A)}$
Reduction of the law of catalysis rate to the law of homogeneous catalysis	$v_{Ho} = \frac{Q_{\Sigma}}{F \bullet t \bullet m_1 \lvert z_1 - z_2 \rvert} = \frac{e \bullet n_a}{F \bullet (\tau_D + \tau_A) \bullet m_1 \bullet \lvert z_1 - z_2 \rvert}$	$Q_{\Sigma} = \frac{e \bullet n_a \bullet t}{(\tau_D + \tau_A)}$
Reduction of the catalysis rate law to the field catalysis law	$v_{Fcat} = \frac{Q_{\Sigma}}{F \bullet t \bullet m_1 \bullet \lvert z_1 - z_2 \rvert} = \frac{e \bullet f_e \bullet E_{cat}}{F \bullet m_1 \bullet \lvert z_1 - z_2 \rvert \bullet E_i}$	$Q_{\Sigma} = \frac{e \bullet f_e \bullet E_{cat} \bullet t}{E_i}$

Formulas (7) and (8) can be presented using the Avogadro constant, taking into account the known relation of the fundamental constants ($F = e \bullet N_A$):

$$v_{cat} = \frac{N_e}{N_A \bullet t \bullet m_1 \bullet |z_1 - z_2|} \qquad (9)$$

$$n_{cat} = \frac{N_e}{N_A \bullet m_1 \bullet |z_1 - z_2|} \qquad (10)$$

Here Ne is the number of electrons obtained (given up) by the reactants during catalysis.

The generalized law of the rate of catalysis turns into the rate laws for heterogeneous, homogeneous, and field catalysis at the corresponding values of Q_Σ:

$$v_{He} = \frac{Q_\Sigma}{F \bullet t \bullet m_1 \bullet |z_1 - z_2|} = \frac{e \bullet n_a \bullet |k_1 - k_2|}{F \bullet (\tau_D + \tau_A) \bullet m_1 \bullet |z_1 - z_2|} \qquad (11)$$

$$v_{Ho} = \frac{Q_\Sigma}{F \bullet t \bullet m_1 |z_1 - z_2|} = \frac{e \bullet n_a}{F \bullet (\tau_D + \tau_A) \bullet m_1 \bullet |z_1 - z_2|} \qquad (12)$$

$$v_{Fcat} = \frac{Q_\Sigma}{F \bullet t \bullet m_1 \bullet |z_1 - z_2|} = \frac{e \bullet f_e \bullet E_{cat}}{F \bullet m_1 \bullet |z_1 - z_2| \bullet E_i} \qquad (13)$$

The generalized formulas for TOF and TON are as follows:

$$TOF_{cat} = \frac{Q_\Sigma}{e \bullet n_a \bullet t \bullet m_1 \bullet |z_1 - z_2|} \qquad (14)$$

$$TON_{cat} = \frac{Q_\Sigma}{e \bullet n_a \bullet m_1 \bullet |z_1 - z_2|} \qquad (15)$$

Generalized formulas (14) and (15) turn into formulas for TOF and TON heterogeneous, homogeneous, and field catalysis at the corresponding values of Q_Σ:

$$TOF_{He} = \frac{|k_1 - k_2|}{(\tau_D + \tau_A) \bullet m_1 \bullet |z_1 - z_2|} \qquad (16)$$

$$TON_{He} = \frac{|k_1 - k_2| \bullet t}{(\tau_D + \tau_A) \bullet m_1 \bullet |z_1 - z_2|} \qquad (17)$$

$$TOF_{Ho} = \frac{1}{(\tau_D + \tau_A) \bullet m_1 \bullet |z_1 - z_2|} \qquad (18)$$

$$TON_{Ho} = \frac{t}{(\tau_D + \tau_A) \bullet m_1 \bullet |z_1 - z_2|} \qquad (19)$$

$$TOF_{Fcat} = \frac{f_e \bullet E_{cat}}{m_1 \bullet |z_1 - z_2| \bullet E_i} \qquad (20)$$

$$TON_{Fcat} = \frac{t \bullet f_e \bullet E_{cat}}{m_1 \bullet |z_1 - z_2| \bullet E_i} \qquad (21)$$

Table 2 presents the generalized TOF formulas and their reduction to particular types of catalysis.

Table 2

Name	**Generalized TOF formulas**	**Note**
TOF_{cat} (turnover frequency)	$TOF_{cat} = \frac{Q_\Sigma}{e \bullet n_a \bullet t \bullet m_1 \bullet \lvert z_1 - z_2 \rvert}$	General formula for TOF
TOF_{He} (turnover frequency)	$TOF_{He} = \frac{Q_\Sigma}{e \bullet n_a \bullet t \bullet m_1 \bullet \lvert z_1 - z_2 \rvert} = \frac{\lvert k_1 - k_2 \rvert}{(\tau_D + \tau_A) \bullet m_1 \bullet \lvert z_1 - z_2 \rvert}$	$Q_\Sigma = \frac{e \bullet n_a \bullet \lvert k_1 - k_2 \rvert \bullet t}{(\tau_D + \tau_A)}$
TOF_{Ho} (turnover frequency)	$TOF_{Ho} = \frac{Q_\Sigma}{e \bullet n_a \bullet t \bullet m_1 \bullet \lvert z_1 - z_2 \rvert} = \frac{1}{(\tau_D + \tau_A) \bullet m_1 \bullet \lvert z_1 - z_2 \rvert}$	$Q_\Sigma = \frac{e \bullet n_a \bullet t}{(\tau_D + \tau_A)}$
TOF_{Fcat} (turnover frequency)	$TOF_{Fcat} = \frac{Q_\Sigma}{e \bullet n_a \bullet t \bullet m_1 \bullet \lvert z_1 - z_2 \rvert} = \frac{f_e \bullet E_{cat}}{m_1 \bullet \lvert z_1 - z_2 \rvert \bullet E_i}$	$Q_\Sigma = \frac{e \bullet f_e \bullet E_{cat} \bullet t}{E_i}$

6. Combined catalysis.

A large number of catalytic reactions take place with the participation of complex catalysts or several catalysts. Combined catalysis is catalysis under the action of a combined catalyst [31, 32]. Additional effects of fields and various types of radiation on the catalyst also belong to combined catalysis. Examples of such reactions are electrocatalysis, photocatalysis, electrostatic catalysis, radiation catalysis, laser catalysis, photocatalysis, electroorganocatalysis, photoorganocatalysis, etc. [7 - 18, 33].

The reaction of A+B = AB when Cat(1) catalyst and Cat(2) field are used together can be represented by the scheme shown in Fig. 5.

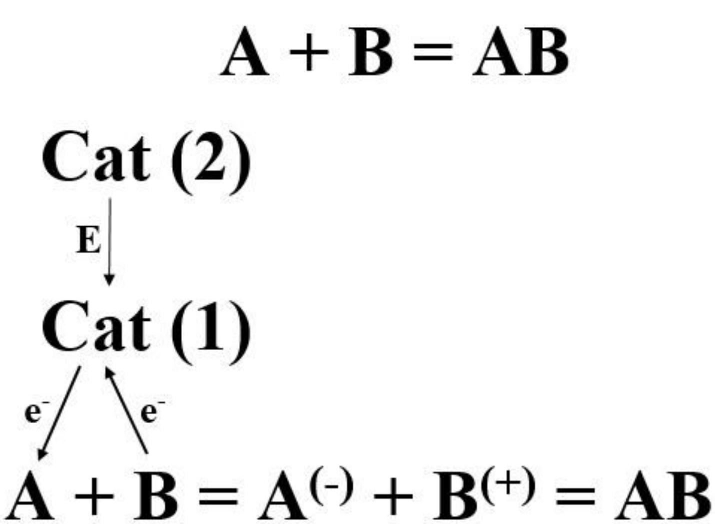

Fig. 5. Scheme of combined field catalysis. A, B - reagents. AB - reaction product. $A^{(-)}$, $B^{(+)}$ - ionized reagents. Cat (1)- first catalyst, Cat (2)- second catalyst (field), E - field energy, e- - electrons.

The reaction of A+B = AB when Cat(1) catalyst and Cat(2) electric current are used together can be represented by the scheme shown in Fig. 6.

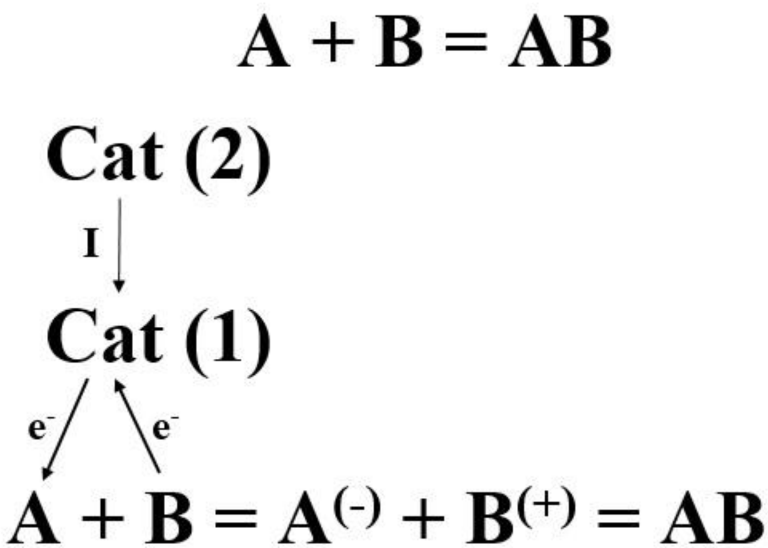

Fig. 6. Scheme of combined electrocatalysis. A, B - reagents. AB - reaction product. $A^{(-)}$, $B^{(+)}$ - ionized reagents. Cat(1)- the first catalyst, Cat(2) - electric current I, e^- - electrons.

The reaction of A+B = AB when Cat(1) catalyst and Cat(2) external irradiation are used together can be represented by the scheme shown in Fig. 7.

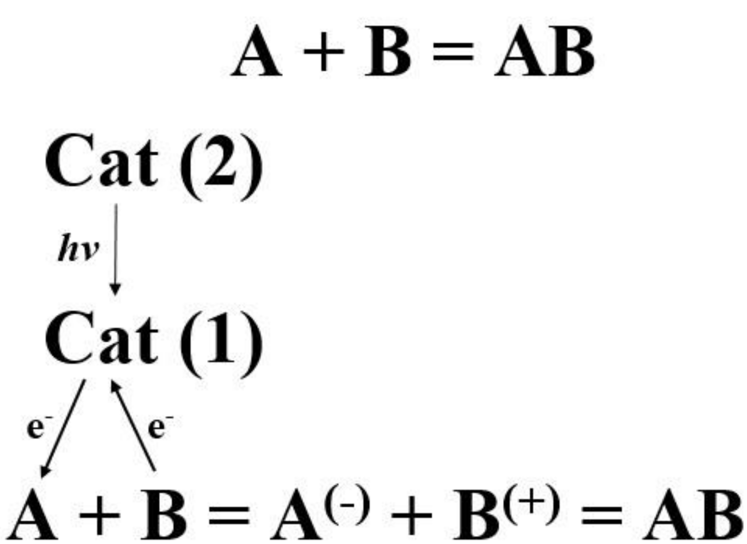

Fig. 7. Scheme of combined photocatalysis. A, B - reagents. AB - reaction product. $A^{(-)}$, $B^{(+)}$ - ionized reagents. Cat(1)- first catalyst, Cat(2) - radiation, hv - photon energy, e^- - electrons.

A new effect - catalytic resonance - was discovered in combined catalysis [34 - 41]. This discovery for the first time demonstrated the possibility of overcoming the Sabatier maximum in catalysis [34 - 41].

7. The universal law of catalysis and the rate law of combined catalysis.

It follows from the law of conservation of electric charge that the laws of combined catalysis are additive laws. The main parameter in them is the total electric charge obtained by the reactants. Accordingly, the value Q_Σ for combined catalysis will be determined by the ratio:

$$Q_\Sigma = \frac{e \bullet n_a \bullet (|k_1 - k_2| + ... + |r_1 - r_2|) \bullet t}{(\tau_D + \tau_A)} \quad (22)$$

where: r_1 is the initial oxidation degree of the r-th catalyst; r_2 is the final oxidation degree of the r-th catalyst.

From the equation of the generalized law of catalysis follows the law of the rate of combined catalysis:

$$v_{Comb} = \frac{Q_\Sigma}{F \bullet t \bullet m_1 \bullet |z_1 - z_2|} = \frac{e \bullet n_a \bullet (|k_1 - k_2| + ... + |r_1 - r_2|)}{F \bullet (\tau_D + \tau_A) \bullet m_1 \bullet |z_1 - z_2|} \quad (23)$$

The ratio for the reaction yield of combined catalysis is as follows:

$$n_{Comb} = \frac{e \bullet n_a \bullet (|k_1 - k_2| + ... + |r_1 - r_2|) \bullet t}{F \bullet (\tau_D + \tau_A) \bullet m_1 \bullet |z_1 - z_2|} \quad (24)$$

8. The universal law of catalysis and Faraday's law

Faraday's law of electrolysis follows directly from the generalized law of catalysis. The total number of N_e electrons involved in electrolysis:

$$N_e = \frac{I \bullet t}{e} \quad (25)$$

Total electric charge:

$$Q_\Sigma = I \bullet t \quad (26)$$

For electrolysis, $m_1 = 1$, $z_2 = 0$. From the generalized law of catalysis (8), taking into account (26), Faraday's law of electrolysis directly follows:

$$n_F = \frac{Q_\Sigma}{F \bullet m_1 \bullet |z_1 - z_2|} = \frac{I \bullet t}{F \bullet m_1 \bullet |z_1 - z_2|} = \frac{I \bullet t}{F \bullet z_1} \quad (27)$$

The transformation of the generalized law of catalysis into Faraday's law of electrolysis shows that electrolysis belongs to the class of catalytic reactions. The catalyst is electrons. The reaction is realized by direct transfer of electrical charges to the reactant. This occurs through the transfer of electrons from the cathode to the reagent and through the reception of electrons by the anode from the reagent. In the donor-acceptor mechanism of electrolysis, the cathode is the electron donor and the anode is the electron acceptor. As in other types of catalysis, the active factor in the reaction is the electric charge.

9. Reduction of the universal law of catalysis to private laws of catalysis.

Table 3 shows the general law of catalysis and its reduction to private laws of catalysis.

Table 3.

Name	**Generalized formulas for catalysis**	**Note**
Generalized law of catalysis and law of heterogeneous catalysis.	$v_{He} = \frac{e \bullet n_a \bullet \lvert k_1 - k_2 \rvert}{F \bullet (\tau_D + \tau_A) \bullet m_1 \bullet \lvert z_1 - z_2 \rvert} = \frac{Q_\Sigma}{F \bullet t \bullet m_1 \bullet \lvert z_1 - z_2 \rvert}$	$Q_\Sigma = \frac{e \bullet n_a \bullet \lvert k_1 - k_2 \rvert \bullet t}{(\tau_D + \tau_A)}$
Generalized law of catalysis and the law of homogeneous catalysis	$v_{Ho} = \frac{e \bullet n_a}{F \bullet (\tau_D + \tau_A) \bullet m_1 \bullet \lvert z_1 - z_2 \rvert} = \frac{Q_\Sigma}{F \bullet t \bullet m_1 \bullet \lvert z_1 - z_2 \rvert}$	$Q_\Sigma = \frac{e \bullet n_a \bullet t}{(\tau_D + \tau_A)}$
The generalized law of catalysis and the law of field catalysis.	$v_{Fcat} = \frac{e \bullet f_e \bullet E_{cat}}{F \bullet m_1 \bullet \lvert z_1 - z_2 \rvert \bullet E_i} = \frac{Q_\Sigma}{F \bullet t \bullet m_1 \bullet \lvert z_1 - z_2 \rvert}$	$Q_\Sigma = \frac{e \bullet f_e \bullet E_{cat} \bullet t}{E_i}$
Generalized law of catalysis and the law of combined catalysis	$v_{Comb} = \frac{e \bullet n_a \bullet (\lvert k_1 - k_2 \rvert + ... + \lvert r_1 - r_2 \rvert)}{F \bullet (\tau_D + \tau_A) \bullet m_1 \bullet \lvert z_1 - z_2 \rvert} = \frac{Q_\Sigma}{F \bullet t \bullet m_1 \bullet \lvert z_1 - z_2 \rvert}$	$Q_\Sigma = \frac{e \bullet n_a \bullet (\lvert k_1 - k_2 \rvert + ... + \lvert r_1 - r_2 \rvert) \bullet t}{(\tau_D + \tau_A)}$
Generalized law of catalysis and Faraday's law of electrolysis	$n_F = \frac{Q_\Sigma}{F \bullet m_1 \bullet \lvert z_1 - z_2 \rvert} = \frac{I \bullet t}{F \bullet m_1 \bullet \lvert z_1 - z_2 \rvert} = \frac{I \bullet t}{F \bullet z_1}$	$Q_\Sigma = I \bullet t; z_2 = 0; m_1 = 1$

The reduction of the general law of catalysis to particular laws of catalysis is shown in Fig. 8.

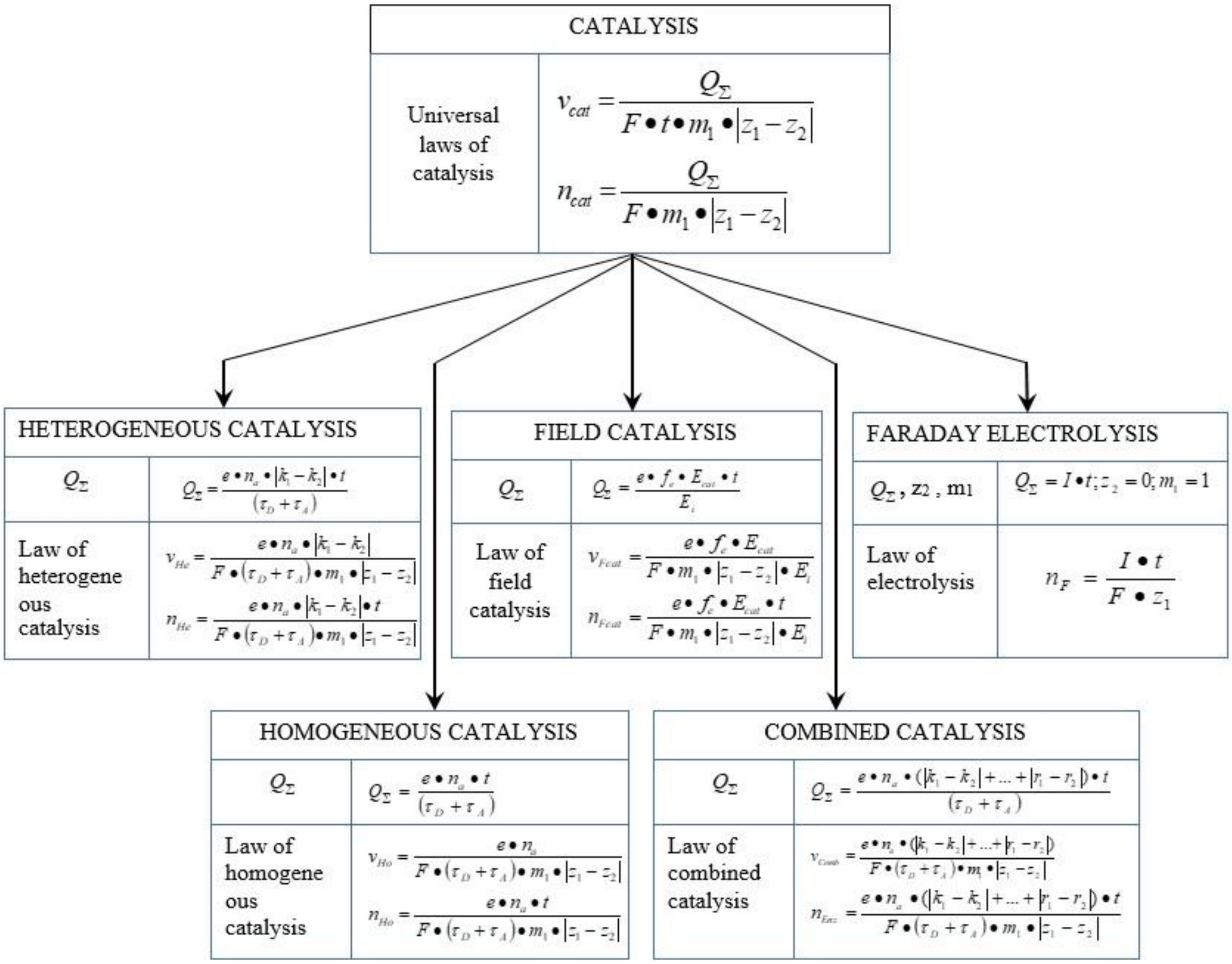

Fig. 8. Reduction of the general law of catalysis to particular laws of catalysis.

The general law of catalysis is a direct consequence of the universal donor-acceptor mechanism of catalysis, which is characteristic of its various types. The same donor-acceptor mechanism underlies Faraday's electrolysis. In all types of catalysis and in electrolysis, there is a change in the oxidation state of the reactants either under the influence of a material catalyst or under the influence of a field or under the influence of an electric current. The change in the oxidation state of the reactants is due to the exchange of electrical charges between the catalyst and the reactants.

10. Conclusion

Instead of studying the interaction on the level of molecules and atoms (the mechanism of intermediate compounds), we investigated the donor-acceptor mechanism, in which the interaction on the level of elementary particles is realized. The study of the mechanism of catalysis on the level of interaction of elementary particles made it possible to reveal the universal acting factor of catalysis. This acting factor in catalysis is the electric charge transferred to the reactants by the catalyst. Electrical charges change the oxidation state of the reactants and accelerate the chemical reaction. The decrease of the energy barrier of the chemical reaction takes place at the fundamental level - at the level of the interaction of electric charges.

The universal nature of the donor-acceptor mechanism of catalysis is confirmed. The donor-acceptor mechanism of catalysis made it possible to obtain a generalized law of catalysis, from which the laws of heterogeneous, homogeneous, combined, field catalysis, and the law of Faraday's electrolysis follow as particular results.

Catalysis belongs to the class of fundamental physical and chemical phenomena. The fundamental status of catalysis is confirmed by the following:

1. In catalytic reactions, the fundamental interaction at the level of elementary particles is realized.

2. The interaction constant in the laws of catalysis has been determined. This interaction constant is the TOF [20].

3. All types of catalysis are subject to a general law from which the laws of heterogeneous, homogeneous, combined, and field catalysis follow as particular results.

4. The equations of the laws of catalysis include the fundamental constants: Faraday's constant, the electric charge of the electron, Avogadro's number.

5. In catalytic reactions, the fundamental law of nature, the law of conservation of electric charge, is fulfilled.

11. Conclusions

1. The law of the rate of catalysis has the following universal formula:

$$\boxed{v_{cat} = \frac{Q_{\Sigma}}{F \bullet t \bullet m_1 \bullet |z_1 - z_2|}}$$

2. The reaction yield of catalysis has the following universal formula:

$$\boxed{n_{cat} = \frac{Q_{\Sigma}}{F \bullet m_1 \bullet |z_1 - z_2|}}$$

3. The laws of heterogeneous, homogeneous, combined, field catalysis, and Faraday's law of electrolysis follow from the universal laws of catalysis as particular results.

4. The main parameter in the generalized laws of catalysis is the electric charge. The interaction of electric charges causes a change in the oxidation state of the reactants and lowers the energy barrier of the reaction.

5. The electric charge transferred to the reactants by the catalyst is the main acting factor in catalytic reactions.

6. In catalysis, the mechanism of interaction of the catalyst with the reactants is realized not at the atomic and molecular level, but at the level of elementary particles - electrons and protons.

7. The donor-acceptor mechanism is the universal mechanism of catalysis. This general mechanism is implemented in various types of catalysis.

8. Catalysis belongs to the class of fundamental physical and chemical phenomena.

9. A change in the oxidation state of reactants under the action of catalysts leads to an increase in their reactivity. The greater the difference in the oxidation states of the reactants, the greater the reactivity of the reactants.

10. The table of the oxidation states of chemical elements becomes a guiding document and a useful aid in catalysis [20, 42].

References

1. Romanovsky B.V. Fundamentals of catalysis: a study guide. – M.:BINOM. Knowledge Lab,2014.
2. Golodets, G. I. Heterogeneous catalytic reactions involving molecular oxygen. United States:N.p., 1983. Web. Chapter 1: Problems of the Theory of Catalysis. Edited by G.I. Golodets.Volume 15, 1983, Pages 6-21.
3. A.Afanas'ev and G.E.Zaikov. IN THE WORLD OF CATALYSIS. The science.M:1977.107 p.
4. Romanovsky B. V. Modern catalysis: Science or art? Soros educational journal. Volume 6.No. 9, 2000, p. 43-48.
5. HETEROGENEOUS CATALYSIS IN PRACTICE, by Charles N. Satterfield, [New York, McGraw-Hill Book Company], 1980. 416 pp. [ISBN] 0-07-054875-F.
6. Robert S. Weber. Perspective: Lies, Damn Lies, and Turnover Rates. Journal of Catalysis.Volume 404, December 2021, Pages 925-928. https://doi.org/10.1016/j.jcat.2021.06.024
7. Max J. Hulsey, Chia Wei Lim and Ning Yan. Promoting heterogeneous catalysis beyond catalyst design Chem. Sci., 2020, 11, 1456-1468. DOI:10.1039/C9SC05947D
8. Fast and Simple Evaluation of the Catalysis and Selectivity Induced by External Electric Fields. Pau Besalu-Sala, Miquel Sola, Josep M. Luis, and Miquel Torrent-Sucarrat. ACS Catal. 2021, 11, 14467−14479. https://doi.org/10.1021/acscatal.1c04247.
9. Che, F.; Gray, J. T.; Ha, S.; Kruse, N.; Scott, S. L.; McEwen, J.-S. Elucidating the Roles of Electric Fields in Catalysis: A Perspective. ACS Catal. 2018, 8, 5153−5174. https://doi.org/10.1021/acscatal.7b02899
10. Aragonès, A., Haworth, N., Darwish, N. et al. Electrostatic catalysis of a Diels–Alder reaction. *Nature* 531, 88–91 (2016). https://doi.org/10.1038/nature16989

11. Max J. Hulsey, Chia Wei Lim and Ning Yan. Promoting heterogeneous catalysis beyond catalyst design Chem. Sci., 2020, 11, 1456-1468. DOI:10.1039/C9SC05947D
12. 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
13. 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
14. 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
15. 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
16. 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
17. 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
18. Kirshenboim O, Frenklah A, Kozuch S. Switch chemistry at cryogenic conditions: quantum tunnelling under electric fields. Chemical Science. 2020. 12: 3179-3187. PMID 34164085 DOI: 10.1039/d0sc06295b
19. Volodymyr Kaplunenko, Mykola Kosinov. ELECTRIC FIELD - IMMATERIAL CATALYST. HTTPS://WWW.RESEARCHGATE.NET/PUBLICATION/361640895_ELECTRIC_FIELD_-IMMATERIAL_CATALYST . DOI: 10.13140/RG.2.2.26019.12320
20. 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
21. Kaplunenko, V., & Kosinov, M. (2022). LAWS OF HETEROGENEOUS CATALYSIS. *InterConf*, (105), 376-398. https://doi.org/10.51582/interconf.19-20.04.2022.037
22. 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
23. Kosinov M., Kaplunenko V. Method of catalysis with the use of carriers of elementary charge - electrons. Patent UA 148668, (2021).
24. Kaplunenko, V., & Kosinov, M. (2022). LAWS OF HOMOGENEOUS CATALYSIS. https://www.researchgate.net/publication/361587838_LAWS_OF_HOMOGENEOUS_CATAL YSIS
25. V. I. Kuznetsov. Development of catalytic organic synthesis. Moscow: - Nauka Publisher. 1964.
26. Kilani, C.B., Batis, H., Chastrette, M., Développement des Idées sur la Catalyse au Début du XIXe Siècle, Actualité Chimique, 44-50, 2001
27. E. N. Eremin. Fundamentals of Chemical Kinetics. Moscow: - Higher School. - 1976.
28. I. M. Kolesnikov. Catalysis in the gas and oil industry.- M. 2012. ISBN 5-93969-021-1.
29. Jia Min Jin. (2022). Catalysis Mechanism and Application of Carbon Gasification Reaction-A Comparison of Two Heterogeneous Catalysis Mechanisms. International Journal of Chemistry; Vol. 14, No. 1; 2022. URL: https://doi.org/10.5539/ijc.v14n1p23
30. Jin, J. M. (2022). Heterogeneous Catalysis Mechanism: A Comparison of Two Heterogeneous Catalysis Mechanisms. European Journal of Applied Sciences, 10(1). 598-607.
31. Liu-Zhu Gong. Asymmetric Organo-Metal Catalysis: Concepts, Principles, and Applications. ISBN: 978-3-527-34592-2. 352 Pages.

32. Dian-Feng Chen and Liu-Zhu Gong. Organo/Transition-Metal Combined Catalysis Rejuvenates Both in Asymmetric Synthesis. *J. Am. Chem. Soc.* 2022, 144, 6, 2415–2437. Publication Date:January 20, 2022. https://doi.org/10.1021/jacs.1c11408)
33. Karolina Zalewska, Miguel M. Santos, Hugo Cruz and Luis C. Branco. Photo-Organocatalysis, Photo-Redox, and Electro- Organocatalysis Processes. September 28th, 2016. DOI: 10.5772/64633)
34. Paul J. Dauenhauer, et. al. DYNAMIC RESONANCE OF HETEROGENEOUS CATALYSIS. Patent WO2020176826 (A1) — 2020-09-03.
35. M. Alexander Ardagh, Omar A. Abdelrahman, and Paul J. Dauenhauer. Principles of Dynamic Heterogeneous Catalysis: Surface Resonance and Turnover Frequency Response. ACS Catalysis, 2019, 9 (8), 6929-6937. DOI: 10.1021/acscatal.9b01606
36. M. Alexander Ardagh, Turan Birol, Qi Zhang, Omar A. Abdelrahman, Paul J. Dauenhauer. Catalytic resonance theory: super Volcanoes, catalytic molecular pumps, and oscillatory steady state. Catalysis Science & Technology 2019, 9 (18), 5058-5076. https://doi.org/10.1039/C9CY01543D
37. M. Alexander Ardagh, Manish Shetty, Anatoliy Kuznetsov, Qi Zhang, Phillip Christopher, Dionisios G. Vlachos, Omar A. Abdelrahman, Paul J. Dauenhauer. Catalytic resonance theory: parallel reaction pathway control. Chemical Science 2020, 11 (13), 3501-3510.https://doi.org/10.1039/C9SC06140A
38. Joshua Gopeesingh, M. Alexander Ardagh, Manish Shetty, Sean T. Burke, Paul J. Dauenhauer, Omar A. Abdelrahman. Resonance-Promoted Formic Acid Oxidation via Dynamic Electrocatalytic Modulation. ACS Catalysis 2020, 10 (17), 9932-9942. https://doi.org/10.1021/acscatal.0c02201
39. Ji Qi, Joaquin Resasco, Hossein Robatjazi, Isabel Barraza Alvarez, Omar Abdelrahman, Paul Dauenhauer, Phillip Christopher. Dynamic Control of Elementary Step Energetics via Pulsed Illumination Enhances Photocatalysis on Metal Nanoparticles. ACS Energy Letters 2020, 5 (11), 3518-3525. https://doi.org/10.1021/acsenergylett.0c01978
40. Shetty, M. et al. (2020). The Catalytic Mechanics of Dynamic Surfaces: Stimulating Methods for Promoting Catalytic Resonance. ACS Catalysis, 10(21), 12666-12695.https://doi.org/10.1021/acscatal.0c03336
41. Wittreich G, Liu S, Dauenhauer P, Vlachos D. Catalytic Resonance of Ammonia Synthesis by Dynamic Ruthenium Crystal Strain. ChemRxiv. Cambridge: Cambridge Open Engage; 2021.
42. Template: List of oxidation states of the elements. https://en.wikipedia.org/wiki/Template:List_of_oxidation_states_of_the_elements#Documentation