Current Perspectives on Chemical Sciences

Vol. 5

Current Perspectives on Chemical Sciences

Vol. 5

Current Perspectives on Chemical Sciences

Vol. 5

Editor(s)

Dr. Wan Mazlina Md Saad

Lecturer,
Department of Medical Laboratory Technology, Faculty of Health Sciences, Universiti Teknologi MARA, Malaysia.
Email: mazlinasaad14@gmail.com, Wanmaz755@salam.uitm.edu.my;

9 789390 516124

9 789390 516131

Contents

A Discussion on the Theory of Conjugate Reactions in the Context of Modern Ideas

Tofik Nagiev[1*]

ABSTRACT

Various types of possible interactions between reactions are discussed. Some of them are united by the general idea of chemical reaction interference. The ideas on conjugated reactions are broadened and the determinant formula is deduced; the coherence condition for chemical interference is formulated and associated phase shifts are determined. It is shown how interaction between reactions may be qualitatively and quantitatively assessed and kinetic analysis of complex reactions with under-researched mechanisms may be performed with simultaneous consideration of the stationary concentration method. Using particular examples, interference of hydrogen peroxide dissociation and oxidation of substrates is considered. The ensemble of reactions is self-organized through the intermediary of general highly active substances. These processes may be accelerated and effectively implemented with the help of catalysts similar to processes, which take part in the living systems. Self-organization of an ensemble of reactions capable of being intensified or weakened and, therefore, inducing chemical interference, may be suggested as the basis for the principle of organization of many enzymatic ensembles.

Keywords: Conjugation; interference; determinant; initiation.

1. INTRODUCTION

Mechanisms of various chemical reactions were studied in depth in the twentieth century. This contributed to the creative development of the theory of conjugate processes. Thus a series of papers [1-6] was devoted to the development of this "half-forgotten branch of chemical kinetics of the past", where "according to N.A. Shilov the concept of interference of chemical reactions is a natural generalization and nontrivial development of the idea of conjugate oxidation reactions"(from the foreword to the monograph by O.M Poltorak [1]). Mechanisms can form the basis for chemical reasoning, allowing the recognition of patterns of reactivity when a new reagent, reaction or processes are presented without the need of blind memorization [7].

However, there is a recent paper [8], claiming development of the theory of conjugate processes, where the "conjugation of elementary stages through general intermediates as a universal phenomenon" is taken as a basis.

This view contradicts one of the basic principles of chemical kinetics—about independence of the course of elementary stages. Therefore, there is a need to consider the main principles of the theory of conjugate reactions in the kinetic aspect. These principles are as following: only gross reactions carried out in open systems can be conjugated, and only they may have common highly active intermediate substances (intermediates) [9]: while such basic principles of chemical kinetics as the law of the masses and the independence of the course of elementary reactions are fulfilled and retain their inviolability. The principal basis for enumerating mechanistic possibilities is accumulated chemical experience with related systems and the inherent structural features of the system [10].

[1]*National Academy of Sciences of Azerbaijan, Baku, Azerbaijan.*
Corresponding author: E-mail: tnagiev@azeurotel.com;

Energy aspect of the conjugate processes is discussed in [11] in the framework of thermodynamics of irreversible processes.

Despite the fact that the basics of conjugate reactions were formulated at the beginning of the 20th century, nowadays they have found their "second wind" as part of the creation of innovative technologies that mimic useful functions of the processes occurring in nature (in particular, enzymatic catalysis). It should be considered that despite the fact that the theory of conjugate reactions was developed at the time when there was almost no information about detailed mechanism of chemical reactions, it nevertheless remains true on its fundamental basis. However, the old theories "cannot be revived to life in their literal interpretation".

Characteristic features of the conjugate reactions formulated by N.A. Shilov in his monograph [9] consist of following regulations:

> - an exergonic reaction performs useful work for the flow of another—endergonic—reaction, i.e. a loss of free energy in a primary reaction fully covers an increase in free energy in a secondary reaction;
> - communication channels between conjugate reactions are established through common intermediate compounds;
> - conjugate reactions necessarily occur in open systems;
> - conjugated reactions must be complex.

We have added to this list a number of classical regulations of chemical kinetics.

It is necessary to add new regulations as Shilov's monograph [9] was published in 1905, when such highly active intermediate substances as free radicals, active complex compounds, etc. were not known. Undoubtedly, in the kinetics of conjugate reactions along with the law of masses, the fundamental chemical postulate of the independence of elementary reactions is unbreakable.

Possibility of occurrence of conjugate reactions only in open systems is associated with the requirement of the system to have a constant mass exchange with external environment. This regulation radically distinguishes conjugate reactions from initiated, catalytic, autocatalytic and polymeric processes that can occur in close systems.

 The fact that conjugate reactions must necessarily be hindered is explained by the fact that only they (because of their complexity) may have common highly active intermediate particles. Here it is necessary to clarify why ordinary elementary stages involved in reaction mechanisms cannot be conjugated to each other: elementary stages of a mechanism of any complex chemical reaction never interfere in each other's flow (otherwise it would contradict the independence of their course); in this case all complex reactions known in chemistry would be conjugate (which is absurd). Only the part of the complex reactions that have common highly active intermediate particles (intermediates) can be conjugate.

The main subject of this article is discussion and terminological clarification of fundamental issues related to the kinetics of interaction of the complex reactions (chemical interference).

However, it is necessary to demonstrate differences between various synchronous (i.e., simultaneously occurring) reactions—parallel, sequential, parallel-sequential, conjugate and coherent-synchronized reactions (see Fig. 1).

Where $A \rightarrow B$ is the primary reaction; $A \rightarrow C$ is the secondary reaction.

As can be seen from the diagram, the most significant distinguishing feature of conjugate and coherently synchronized reactions from other reactions is their coherence (consistency).
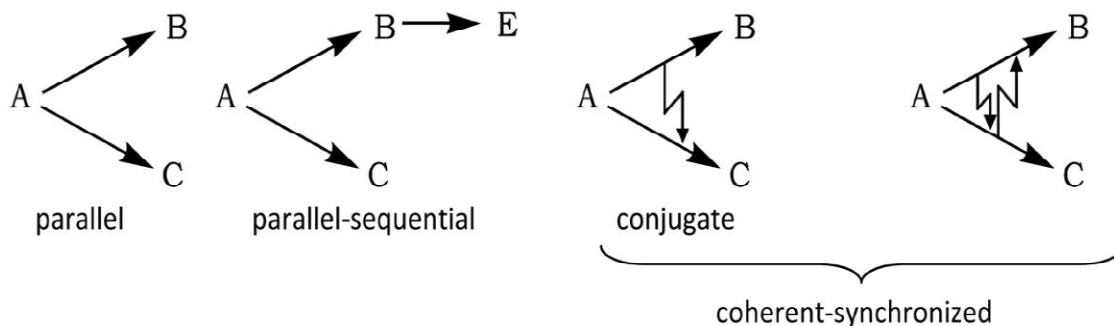
It is necessary to consider the regulations stated below in order to understand these differences:
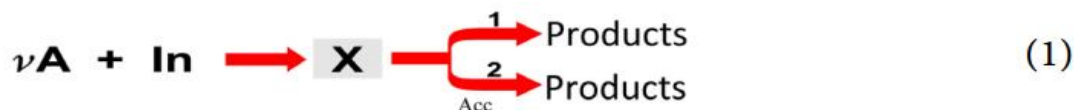
> ➤ the secondary (target) non-induced reaction is a non-spontaneous or self-induced reaction, which is difficult to realize due to kinetic and thermodynamic order;
> ➤ during induction, type of the target (secondary) reaction is transformed from non-spontaneous to self-induced and, under realizable conditions, it flows without difficulty;
> ➤ a gross equation of the secondary reaction is already formed in its induced form, i.e. in a transformed form;
> ➤ in contrast to parallel, sequential and parallel-sequential reactions, an induced (secondary) reaction cannot be carried out separately from the primary reaction;
> ➤ the spontaneous target reaction can also be modified under influence of induction and under certain conditions proceed with a high rate;
> ➤ the reaction system, in which chemical induction is realized, contains two or more components.

The concept of chemical interference is put forward by us, as a phenomenon consisting in the fact that reactions occurring synchronously in a chemical system, can mutually strengthen and weaken, and in this state they are necessarily coherent [1-6].

Mathematical apparatus of the chemical interference and, in particular, coherent-synchronized reactions

Fig. 1. Synchronized chemical reactions

$$\nu A + In \longrightarrow X \overset{1}{\underset{2}{\longrightarrow}} \begin{matrix} \text{Products} \\ \text{Products} \end{matrix} \qquad (1)$$

(where A is an actor, In is an inductor, Acc is an acceptor and X is a highly active particle) consists of the determinant equation [1-6]:

$$D = \nu\left(f_{A_1}/f_{Acc} + f_{A_2}/f_{acc}\right)^{-1} \quad \text{or} \quad D = \nu\left(r_{A_1}/r_{Acc} + r_{A_2}/r_{Acc}\right)^{-1} \qquad (2)$$

(where r_{A_1}, r_{A_2} are the rates of the primary – 1 and the secondary – 2 reactions, f_{A_1} and f_{A_2} are the actor consumption in the primary and secondary reactions) and the coherence ratio:

$$\frac{1}{\nu}f_A = f_{In} = f_{A_1} + f_{A_2} = f'_{A_1} + f'_{A_2} = f''_{A_1} + f''_{A_2} \qquad (3)$$

On the basis of these equations, a determinant scale was compiled. It is easy to determine in the reaction medium the nature of an intervention of one reaction into another (chemical interference) using this scale:

$D = 0 \div v$ is the area of chemical conjugation; $D > v$ is the area of other interrelated interfering reactions.

The scheme shows that the synchronous reactions which are not coherent, but one interferes with another, can be present in the chemical system (for example, initiated, catalytic and autocatalytic reactions, etc.).

A kinetic study of the chemical system where an interaction of reactions takes place, allows us to make a choice between various types of interfering chemical reactions on the basis of experimental data. Therefore, the study of chemical interference may be useful in an investigation of mechanisms of complex reactions.

In this respect, a determinant equation is an easily adaptable kinetic apparatus for solving complex chemical problems.

Thus, the determinant equation and a scale of chemical interference built on its basis make it easy to distinguish conjugate and coherent synchronous reactions from catalytic, initiated, free-radical reactions, autocatalytic and other reactions, which is practically difficult to do.

2. COHERENT SYNCHRONIZED OXIDATION REACTIONS BY HYDROGEN PEROXIDE

The examples given below – methane oxidation to methanol, ethylene oxidation to acetaldehyde and ethanol, propane oxidation to isopropanol, propylene epoxidation and hydroxylation, and ethanol oxidation to acetaldehyde – demonstrate experimental approaches to the study of interfering reaction dynamics and, with the help of the determinant equation, the potential abilities of the reaction media are assessed, and the type of chemical interference, determined.

2.1 Methane Oxidation

The monooxygenase reaction for synthesizing methanol from methane was studied in the presence of cytochrome P-450 biosimulators, such as ferroprotoporphyrin catalysts with carriers (Al_2O_3, NaX, aluminum-chromium-silicate or aluminum-magnesium-silicate). This reaction helped in the detection of the highest catalytic activity for $PPEe^{3+}OH$/aluminum-magnesium-silicate [1-3], which also displayed the highest catalytic activity for the hydroxylation reaction. As shown, the optimal hydroxylic activity of the catalyst is displayed in the initial 30 min of its operation (methanol output equals 60 wt.%, selectivity is 97 wt.%). Fig. 2.1 shows that the kinetic dependence of the methanol output on the temperature has a maximum at 180°C and that the curve of the molecular oxygen yield has a corresponding minimum. In this experiment, the methanol yield reaches 46.5 wt.%, at which the methane conversion rises to 48wt.%. The nontarget products CH_2O and HCOOH in low amounts (- 1.5%) and temperature have no effect on their yield. Its value (f_{In}) obeys the main coherence condition following from equation (1.8). More precisely, $f_{In} \approx const$ for current reaction conditions. This value may be simply calculated from the data of Fig. 2.1a. A graphical presentation of chemical interference, shaped as asymptotically approaching curves in another range of the reaction conditions, is plotted in Fig. 2.1b.
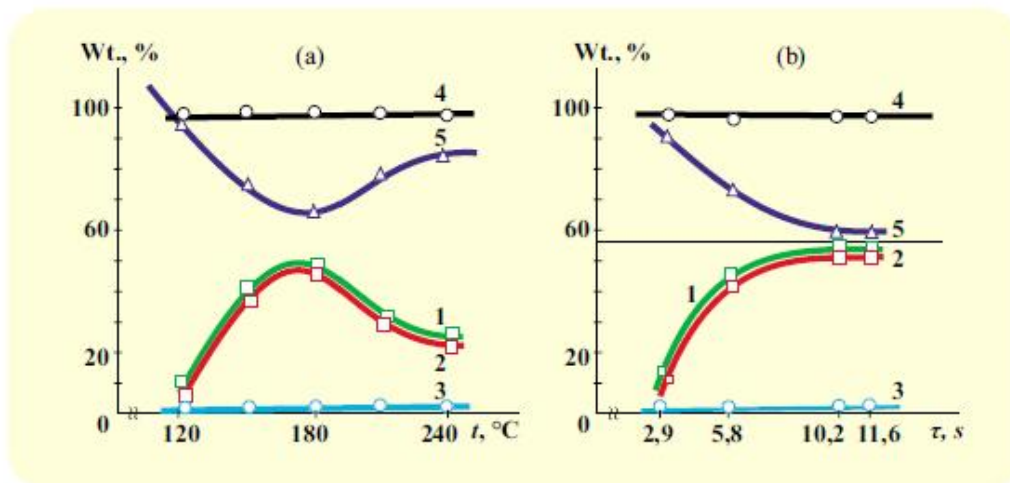
Fig. 2.1. Dependencies of methane hydroxylation outputs on (a) temperature and (b) contact time at 180°C.1: CH_4 conversion; 2: CH_3OH output; 3: CH_2O and HCOOH outputs; 4: selectivity; 5: O_2 output ratios: $CH_4:H_2O_2$ = 1:1.4 (a) and 1:1.8 (b); $V_{CH_4}V_{H_2O_2}$ = 0.8 ml/h, $[H_2O_2]$ = 20 wt.%.

In the chemical system studied, a biosimulator catalyzes two interrelated (catalase and monooxygenase) reactions, which are synchronized and proceed according to the Fig. 2.2, where ImtOH is a $PPFe^{3+}OH/AlMgSi$ biosimulator, and ImtOOH is a $PPFe^{3+}OOH/AlMgSi$ intermediate compound: (1) primary catalase reaction and (2) hydroxylation (secondary monooxygenase reaction).

Both reactions (1) and (2) in the scheme proceed via a general $PPFe^{3+}OOH/AlMgSi$ intermediate compound, which is certainly the transfer agent for the inductive action of the primary reaction on the secondary reaction. The determinant, which allows the quantitative identification of the interaction between reactions, equals D=0,48.
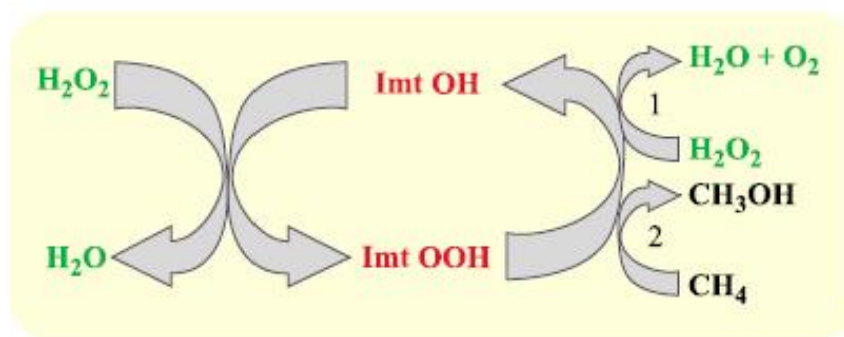
Fig. 2.2. Mechanism of the coherent-synchronized catalase and monooxygenase ($CH_4+H_2O_2=CH_3OH+H_2O$) reactions.

This indicates that reactions (1) and (2) are conjugated because the value obtained on the determinant scale of chemical interaction falls within the range of chemical conjugation (D<1) because in the current case, v=l.

Let us consider the experimental data shown in Fig. 2.3a and b, obtained for the homogeneous gas-phase oxidation of methane (or natural gas) by hydrogen peroxide to methanol under pressure [4]. The increase in contact time to 0.95 s (Fig. 2.3a) gives a maximum methanol output and a minimum oxygen output. A further increase in the contact time reduces the methanol output, whereas the molecular oxygen output increases. A similar kinetic regularity is observed in experiments with variable pressure (Fig. 2.3b).

Thus, a comparison of the curves of molecular oxygen accumulation and CH_4 consumption (or CH_3OH accumulation) shows that the maximum CH_4 transformation corresponds to the minimum O_2 accumulation.

Chemical interference is clearly displayed owing to the almost 100% selectivity of the reactions: increased O_2 synthesis induces a simultaneous decrease in CH_4 transformation to CH_3OH, and vice versa.
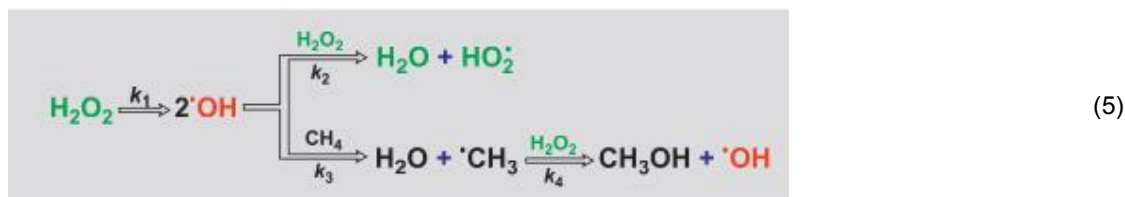
As the curves in Fig. 2.3a and b are considered from positions of coherence and possible phase shift, note that the particular reaction mixture differs from the mixtures considered above by a relatively low (approximately 20 wt.%) CH_4 substrate conversion, although the H_2O_2 dissociates almost completely. This circumstance must be taken into account in the framework of the approach to such a case described above.

The chemical interference determinant can be experimentally determined by the following equation (4).

$$D = v\left(\frac{f_{A_1}}{f_{Acc}} + \frac{f_{A_2}}{f_{Acc}}\right)^{-1}$$

or

$$D = v\left(\frac{r_{A_1}}{r_{Acc}} + \frac{r_{A_2}}{r_{Acc}}\right)^{-1}$$

(4)

For the current conditions of minimal O_2 and maximal CH_3OH outputs, D = 0.18.. It quantitatively characterizes the inductive action of H_2O_2 on CH_4 oxidation and indicates the presence of high potential abilities to increase the induction effect of the system studied (theoretically, in the current case, D may increase to 1 or will tend to approach at least the 50% level). There are physicochemical experimental techniques that allow the manipulation of conjugating reaction rates. On the other hand, not applying the method of stationary concentrations, the determinant equation (4) provides an opportunity to analyze the kinetics of complex reactions with insignificantly studied mechanisms. For these two reactions, the conjugation mechanism is:

$$H_2O_2 \xrightarrow{k_1} 2\,^{\cdot}OH \begin{cases} \xrightarrow[k_2]{H_2O_2} H_2O + HO_2^{\cdot} \\ \xrightarrow[k_3]{CH_4} H_2O + {}^{\cdot}CH_3 \xrightarrow[k_4]{H_2O_2} CH_3OH + {}^{\cdot}OH \end{cases}$$

(5)

$$r_{Acc(CH_4)} = \frac{D}{v}\left(r_{A_1} + r_{A_2}\right)$$

or

$$r_{CH_4} = \frac{D}{v}\left(k_2[H_2O_2] + k_3[CH_4]\right)[OH]$$

(6)

Using experimentally obtained values of r_{CH4} and D [4], the appropriate kinetic calculations were carried out. Therefore, equation (6) adequately describes the kinetics of interfering reaction (5).
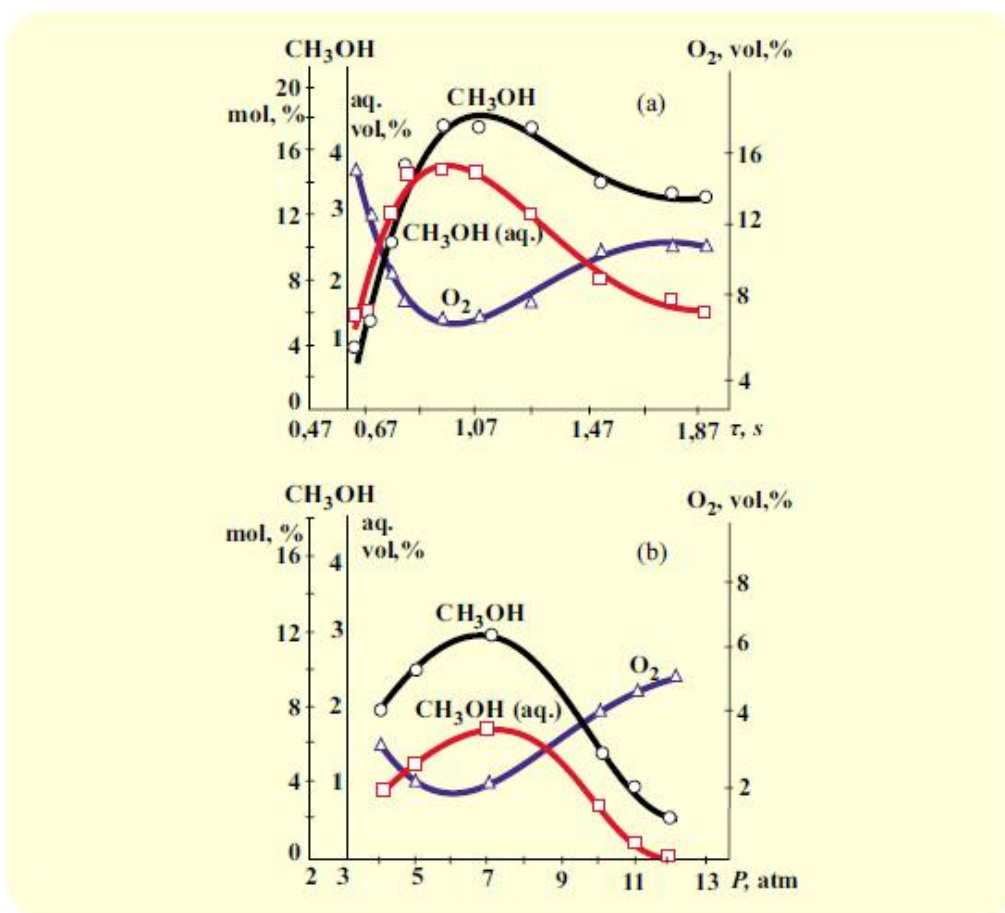
Fig. 2.3. Dependence of methanol output on the contact time (a) and pressure (b); T=400°C и [H$_2$O$_2$] = 30 wt.%; a) p=7 atm, V_{CH_4}=31,4 l/h, $V_{H_2O_2}$=0,18 l/h, CH$_4$:H$_2$O$_2$=1:1,4 (mol) and (б) $V_{H_2O_2}$=0,18 l/h, V_{CH_4}=62,4 l/h, CH$_4$:H$_2$O$_2$ =1:0,4 (mol)

Thus, the determinant equation was found to be useful for the analysis of the kinetics of complex reactions in that it made simpler the kinetic calculations in the determination of the kinetic model of interrelated and synchronized reactions proceeding in the reaction mixture, as well as the qualitative and quantitative assessment of the chemical interference itself.

2.2 Propylene Epoxidation

The diagrams in Fig. 2.4 illustrate the conjugation of two reactions: H$_2$O$_2$ dissociation and propylene epoxidation by hydrogen peroxide [5]. The rate decrease in biosimulator catalase activity product (O$_2$) accumulation is accompanied by a rate increase in epoxidation product synthesis, and these processes interfere via a general highly active intermediating compound, per-FTPhFe^{3+}OOH/Al$_2$O$_3$.

However, presenting the interference picture via a diagram has several principal disad-vantages: 1. diagrams do not show how coherence is implemented; 2. Phase shifts may not be shown; 3. maxima

and minima in the accumulation of the pro ducts of both reactions are not shown; and 4. there is an absence of asymptotic curves.

The advantage of the diagrams is that they are highly illustrative of the chemical conjugation between current reactions. Thus, diagrams help in demonstrating one of the aspects of chemical interference associated with the conjugation of the processes.

2.3 Ethylene Oxidation

The gas-phase monooxidation of ethylene by hydrogen peroxide on a bio - mimetic heterogeneous catalyst (per-FTPhPFe^{3+}OH/Al$_2$O$_3$) was studied under comparatively mild conditions. The biomimetic oxidation of ethylene with hydrogen peroxide was shown to be coherently synchronized with the decomposition of H$_2$O$_2$. Depending on the reaction medium conditions, one of two desired products was formed, either ethanol or acetaldehyde.

In recent years, there has been considerable progress in studies related to the synthesis and development of biomimetic catalysts based on iron porphyrin complexes [1,2,5]. They simulate the main characteristics of enzymes (activity, selectivity, softness of conditions, mechanism of active center operation, etc.), in particular, cytochrome P-450.
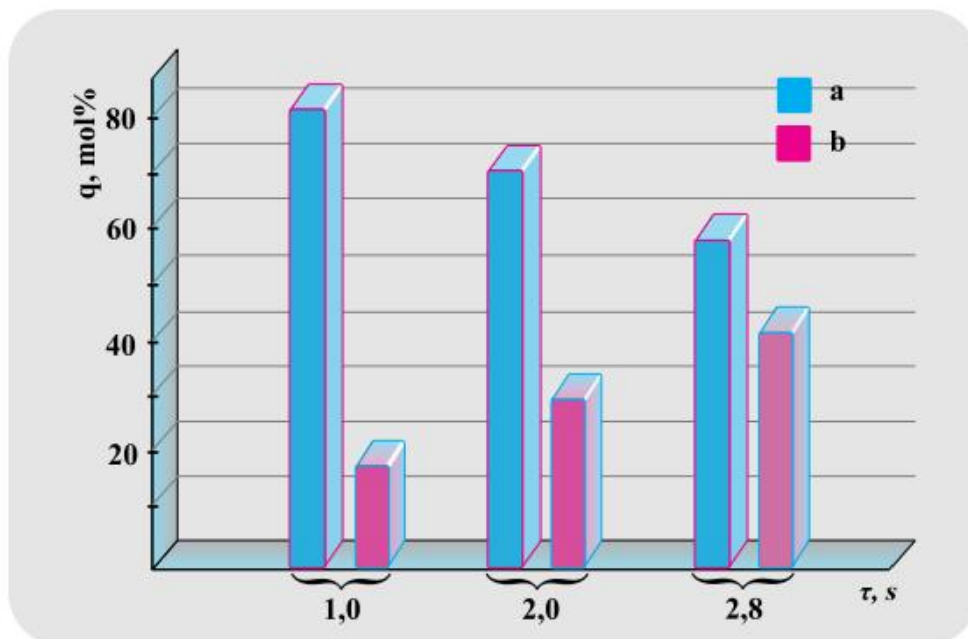
Fig. 2.4. Hydrogen peroxide consumption (q) in catalase (a) and monooxygenase (b) reactions with time of contact; T = 200°C, C$_3$H$_6$:H$_2$O$_2$=1:1,2 (mol)

Distinct from the known homogeneous catalysts modeling cytochrome P-450, heterogeneous iron porphyrin biomimetic catalysts of gas-phase monooxidation possess many technological advantages. For instance, the high-efficiency epoxidation and hydroxylation reactions are performed in the gas phase. This allows many factors to be excluded that substantially influence the catalyst activity in liquid-phase oxidation (the nature of the solvent, reaction medium pH, etc.). In addition, the high selectivity of the processes in these works was also provided by the use of hydrogen peroxide as an oxidizer. As is known [1], hydrogen peroxide satisfies the requirements of the concept of "green

chemistry" and is called a "green oxidizer." It follows that most of the organic reactions with the participation of hydrogen peroxide occur synchronously with its decomposition under coherent conditions of mutual strengthening and weakening. Thanks to the acid-base nature of the carrier (Al_2O_3) of the per-FTPhPFe^{3+}OH/Al_2O_3 biomimetic catalyst, the mechanism of the coherently synchronous monooxidation of ethylene is considered in terms of the concepts accepted for redox enzymatic reactions.

The temperature dependences of the yields of the coherently synchronous ethylene oxidation and hydrogen peroxide decomposition products, C_2H_5OH, CH_3CHO, O_2 and CO_2, are shown in Fig. 2.5. It follows from these dependences that the highest yield of ethanol is obtained at 120°C. An increase in temperature noticeably decreases the yield of ethanol because of its transformation into acetaldehyde. These experimental data well agree with the results obtained in [5], where the peroxidase oxidation of ethanol into acetaldehyde was studied. Note that, at a low temperature, the yield of molecular oxygen is maximal; that is, the catalase reaction with the production of molecular oxygen largely occurs. The yield of O_2 decreases as the temperature increases and is stabilized after a certain temperature is reached. The catalase reaction then has the lowest rate. Simultaneously, the conversion of ethylene into monooxide compounds is stabilized. This is evidence that, at the temperatures specified, the concentration of hydrogen peroxide is insufficient for the catalase reaction deepening and, therefore, ethylene monooxidation. The highest yield of acetaldehyde is limited to 35 wt.%, at 200°C.
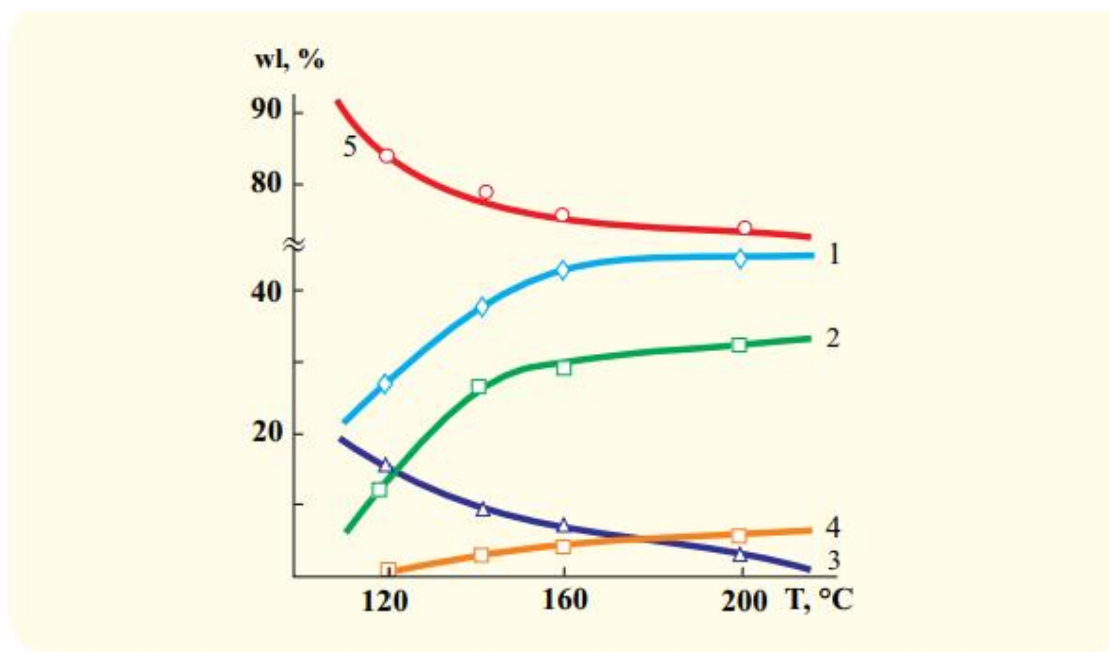
Fig. 2.5. Temperature dependences of the yields of the ethylene monooxidation products at $C_{H_2O_2}$=30%, $W_{C_2H_4}$=0,22 l/h и C_2H_4:H_2O_2 =1:1,2; (1) conversion of C_2H_4, (2) yield of CH_3CHO, (3) yield of C_2H_5OH, (4) yield of CO_2, and (5) yield of O_2.

This conclusion is substantiated by studies of the process depending on the concentration of H_2O_2 in aqueous solution (Fig. 2.6). At a concentration of H_2O_2 above 25%, we observe a synchronous increase in the rates of the ethylene monooxidation and catalase reactions.
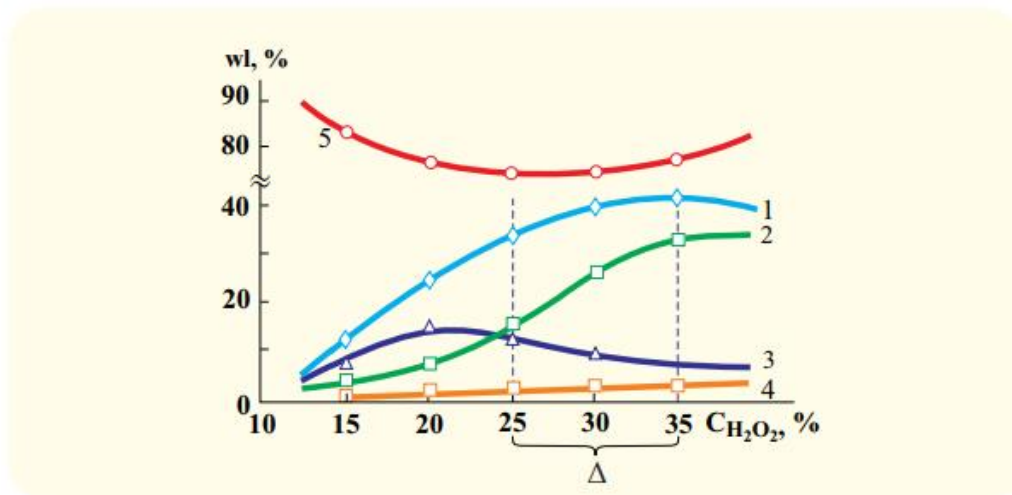
Fig. 2.6. Dependences of the yields of the ethylene monooxidation products on the concentration of the aqueous solution of hydrogen peroxide $C_{H_2O_2}$ at 140°C, $W_{C_2H_4}$=0.22 l/h, and $W_{H_2O_2}$= 1.72 ml/h; (1)-(5) see Fig. 2.5.

The dependences of the yields of the monooxidation reaction products on the concentration of H_2O_2 show that a 20% concentration of H_2O_2 is optimal for ethanol formation (15 wt. %). Higher H_2O_2 concentrations promote the oxidation of ethanol to acetaldehyde. Note that, in the presence of 35 wt. % H_2O_2 at 140°C, the yield of acetaldehyde is at its maximum, 35 wt. %.

It follows from Fig. 2.6 that the monooxidation reaction has a nontrivial feature and that the direction of the reaction can be finely tuned by taking into account the kinetics of the coherently synchronized processes. For instance, on the one hand, the process can be directed toward the selective formation of the monooxidation products by increasing the temperature and simultaneously decreasing the concentration of H_2O_2. On the other hand, at lower temperatures and high hydrogen peroxide concentrations, we also observe the selective formation of the monooxidation products. The kinetics of these two synchronous reactions are determined by their coherence.

The yields of the monooxygenase products and molecular oxygen depending on the contact time τ are shown in Fig. 2.7 (curves 1 and 5). At short contact times, the monooxidase activity is low, and catalase activity prevails. The yield of molecular O_2 decreases as τ increases. Accordingly, the rate of ethylene transformation into monooxide compounds, C_2H_5OH and CH_3CHO, grows.

Under experimental conditions in the absence of the substrate, the reaction goes to completion, and H_2O_2 fully decomposes to H_2O and O_2. It follows from the kinetic data presented in Figs. 2.5–2.7 that kinetic curves 1 and 5 (the catalase and monooxidase reactions) are coherently synchronized. For instance, according to Figs. 2.5 and 2.7, the lowest yield of the monooxygenase products corresponds to the highest yield of O_2, and the two curves (Figs. 2.5 and 2.7) asymptotically approach each other with a very insignificant phase shift Δ [2].

According to Fig. 2.6, the amounts of primary reaction products decrease as the secondary reaction products are accumulated, and both curves have extrema. The minimum of kinetic curve 5 (catalase reaction) corresponds to the maximum of the monooxygenase reaction (kinetic curve 1). If the monooxygenase reaction (curve 1), for kinetic reasons, is synchronized with the primary catalase reaction (curve 5) with some delay, phase shift Δ appears (shown in Fig. 2.6 by a dashed line). The maximum of this curve is slightly shifted to the right by the phase shift Δ value. In other words, the

phase shift corresponds to the difference between the minimum of the kinetic curve of the primary reaction and the maximum of the secondary reaction.
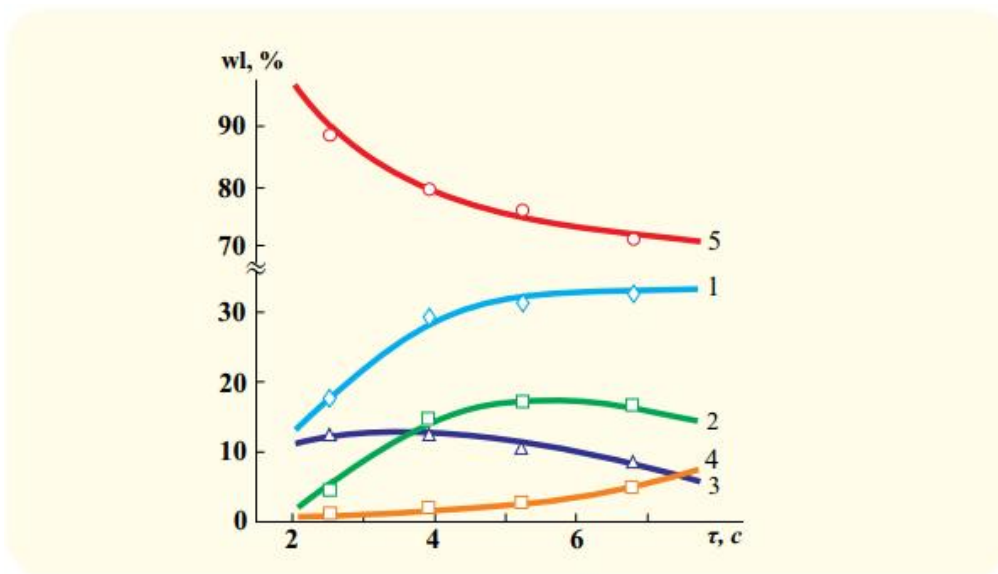

Fig. 2.7. Dependences of the yields of ethylene monooxidation products on contact time (τ) at 140°C, $C_{H_2O_2}$=25%, $W_{C_2H_4}$=0.22 l/h, and $W_{H_2O_2}$=1.72 ml/h; (1)–(5) see Fig. 2.5.

Studies of the monooxygenase activity of the per-FTPhPFe^{3+}OH/Al$_2$O$_3$ biomimetic allow us to flexibly control this complex reaction toward the predominant formation of either ethanol or acetaldehyde. At 120°C, a 30% H_2O_2 concentration, a 1:1.7 C_2H_4:H_2O_2 molar ratio, and C_2H_4 and H_2O_2 flow rates of 0.22 1/h and 1.72 ml/h, respectively, the highest yield of ethanol (15.4 wt. %; the yield of acetaldehyde was 12 wt. %) was obtained. Conversely, at 200°C, the yield of acetaldehyde was 34.6 wt. %, and the yield of ethanol, 4.6 wt. %. Each monooxygenase reaction product is a desired product, and the selectivity of the process under the conditions of a maximum yield of ethanol and a minimum yield of acetaldehyde was almost 100 wt. % based on the monooxygenase products. The selectivity was slightly lower (87 wt. %) under the conditions of obtaining a maximum yield of acetaldehyde because of the formation of CO_2 as a side product.

It follows from the experimental data that the two synchronous reactions, catalase and monooxygenase, interact with each other. As a result, chemical interference is observed in the system, and the primary reaction strengthens the secondary one, which, in turn, decelerates the primary reaction. It follows that the synchronous reactions are coherent, and, most importantly, the coherence condition.

$$f_{H_2O_2}^{0} = f_{1,H_2O_2} = f_{2,H_2O_2} = const, \tag{7}$$

After the calculations of the experimental f_{1,H_2O_2} (0.84, 078, 0.76, and 0.73 mole fractions) and f_{2,H_2O_2} values (0.16, 0.22, 0.24, and 0.23 mole fractions) for experiments with different hydrogen peroxide concentrations (Fig. 2.6, curves 1 and 5) and the substitution of these values into Eq. (7), we see that the coherence condition is satisfied, 0.84 + 0.16 = 0.78 + 0.22 + 0.76 + 0.24 = 0.77 + 0.23 = 1.

It follows that the reaction system includes two coherently synchronous reactions, catalase and monooxidase [1,12]. According to the generally accepted mechanism [3], both reactions occur via a common intermediate, per-FTPhPFe^{3+}OOH/Al$_2$O$_3$, which transfers the inductive action of the primary reaction to the secondary one, that is, the process occurs under bifurcation conditions. This mechanism of the action of two complex reactions is based on the concept that the decomposition of hydrogen peroxide (the primary reaction) accelerates the secondary reaction of olefin monooxidation, and, conversely, the secondary reaction decelerates the formation of the primary reaction products by its occurrence. Such a chemical interaction of the reactions results in chemical interference in the dynamic (that is, time) mode. The effectiveness of the chemical interference in this reaction system is measured by its quantitative characteristic, as determined by the determinant equation.

The experimental determinant value for the optimum regime of the oxidation of C$_2$H$_4$ (200°C, 30% C$_2$H$_4$, and C$_2$H$_4$ and H$_2$O$_2$ flow rates of 0.22 1/h and 1.72 ml/h, respectively) is in the region of chemical conjugation according to the chemical interference determinant scale, when only the inductive action of the primary on the secondary reaction is taken into account.

2.4 Propane Hydroxylation

Synchronizing hydroxylation and hydrogen peroxide decomposition with the use of a biomimetic catalyst allows these reactions to be performed under mutual intensification and weakening conditions (chemical interference) and the rates of these reactions to be easily controlled under comparatively mild conditions. We used this nontraditional chemical experiment technology for hydroxylating propane with hydrogen peroxide to isopropyl alcohol in the presence of a biomimetic catalyst, namely, iron(III) perfluorotetraphenylporphyrin deposited on alumina [5].

The dependences of the yields of isopropanol (i-C$_3$H$_7$OH) and molecular oxygen (O$_2$) in the oxidation of propane (C$_3$H$_8$) on the contact time т are shown in Fig. 2.8. It follows that the hydroxylating activity of the biomimetic is low at small т (т < 0.6 s), whereas, according to the O$_2$ yield curve, the catalase activity prevails. The yield of i-C$_3$H$_7$OH and, accordingly, the conversion of C$_3$H$_8$ increases as т grows. Starting with т = 1.1 s, the synchronization of the catalase and monooxygenase reaction curves becomes obvious. The O$_2$ yield curve for the catalase reaction shows that, at short т, virtually complete catalytic decomposition of H$_2$O$_2$ with the formation of O$_2$ occurs because the rate of propane hydroxylation is then insignificant. The yield of i-C$_3$H$_7$OH increases and reaches a maximum at т = 1.1 s as the consumption of H$_2$O$_2$ in the catalase reaction decreases. Further increasing т causes the synchronization of the yields of the catalase and monooxygenase reaction products. Clearly, this is evidence of the interaction (conjugation) of these two reactions. Note that the complete consumption of hydrogen peroxide was observed in the entire range of the contact time variation. This consumption was distributed between the catalase and hydroxylation reactions according to their kinetics.

The temperature dependences of the yields of i-C3H$_7$OH and O$_2$ are shown in Fig. 2.9. The yield of i-C$_3$H$_7$OH increases as the temperature rises, and the optimal temperature range for the formation of i-C$_3$H$_7$OH is 240–270°C. Note that the yield of i-C$_3$H$_7$OH is stabilized starting at 240°C and that the yields of the products of both reactions differ insignificantly (within ≈5 mol%). At the same time, the yield of O$_2$ exhibits a tendency to stabilize in the specified temperature range. Clearly, this is evidence that the catalase reaction occurs at a minimum rate. Primarily, the stabilization of the yields of i-C$_3$H$_7$OH and O$_2$ shows that, at these temperatures, the concentration of hydrogen peroxide that we use is insufficient for intensifying the catalase and, possibly, hydroxylation reactions. Such dependences are evidence that both reactions (catalase and hydroxylation) not only occur synchronously but also coherently interact with each other. The experimental data on the consumption of hydrogen peroxide in synchronized reactions are shown in Fig. 2.10. These curves are actually very similar to those in Fig. 2.10, except that in Fig. 2.9, the total consumption of H$_2$O$_2$ in the two reactions equals the initial amount of hydrogen peroxide. This leads us to conclude that, under the given conditions, the sum of the yields of the final products of the synchronous reactions corresponds to a constant consumption of H$_2$O$_2$ (actor), and, in our experiments (where H$_2$O$_2$ is completely consumed in the two reactions), the following equation is valid:

$$N_0 = N_1 + N_2 = \text{const.} \tag{8}$$

where N_0 is the initial amount of hydrogen peroxide consumed in both reactions, and N_1 and N_2 are the amounts of hydrogen peroxide consumed in the catalase and monooxygenase reactions, respectively.
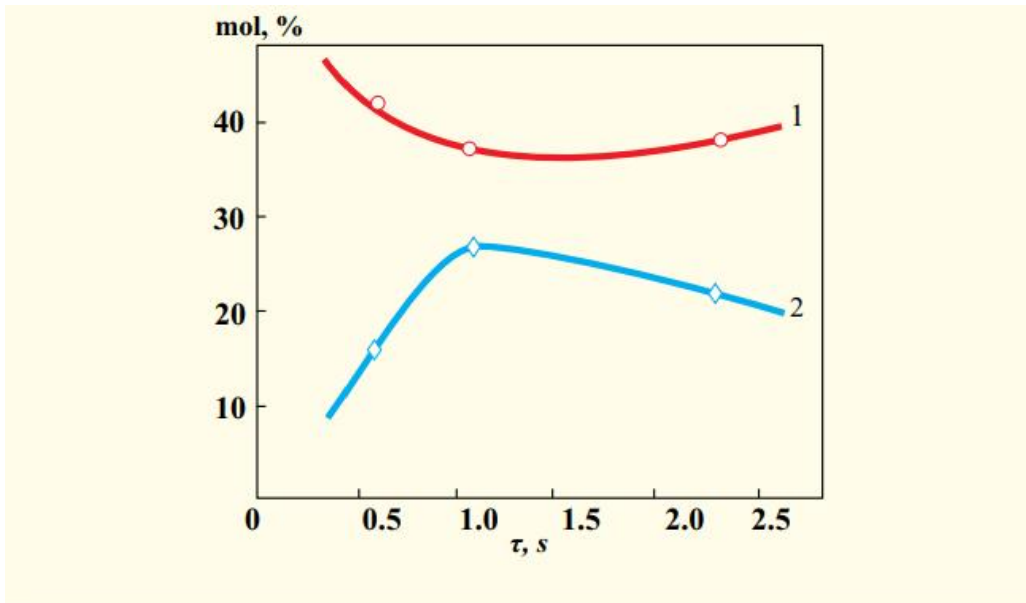
Fig. 2.8. Contact time dependences of reaction product yields:

(1) O_2 and (2) i-C_3H_7OH (240°C, [H_2O_2]=20 wt. %, C_3H_8:H_2O_2 = 1:2).
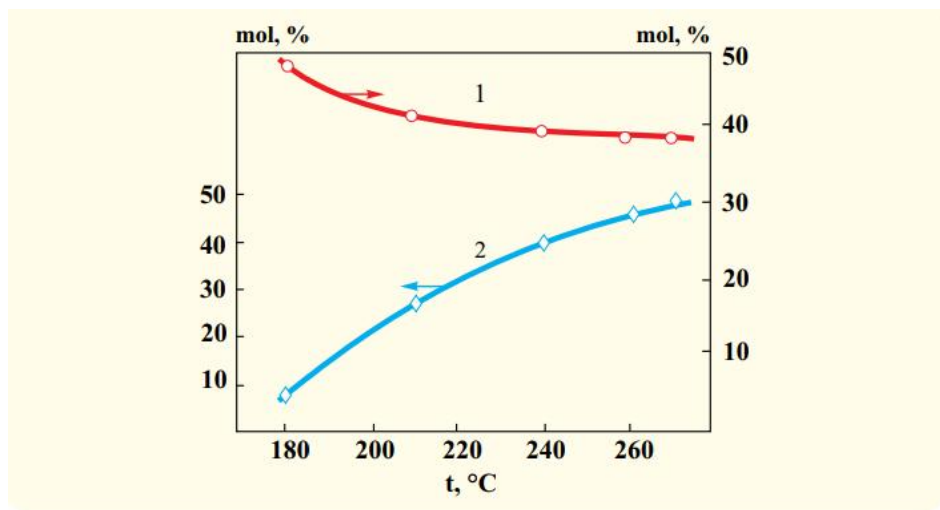
Рис. 2.9. Temperature dependences of reaction product yields ((1) O_2 and

(2) *i*-C_3H_7OH) [H_2O_2] = 20 wt. %, C_3H_8:H_2O_2 =1:2,=0.3 l/h, $v_{C_3H_8}$=4.24 ml/h, τ= 1.2 s).

In agreement with the theory of interactions between synchronous reactions [1,6], it follows from (8) that the condition of the coherence of chemical interference is met in the process under consideration. Because of the coherent interactions of two synchronous reactions, the rate of one of them (catalase

reaction) decreases, whereas that of the other reaction synchronized with the first one (hydroxylation reaction) increases, and vice versa.
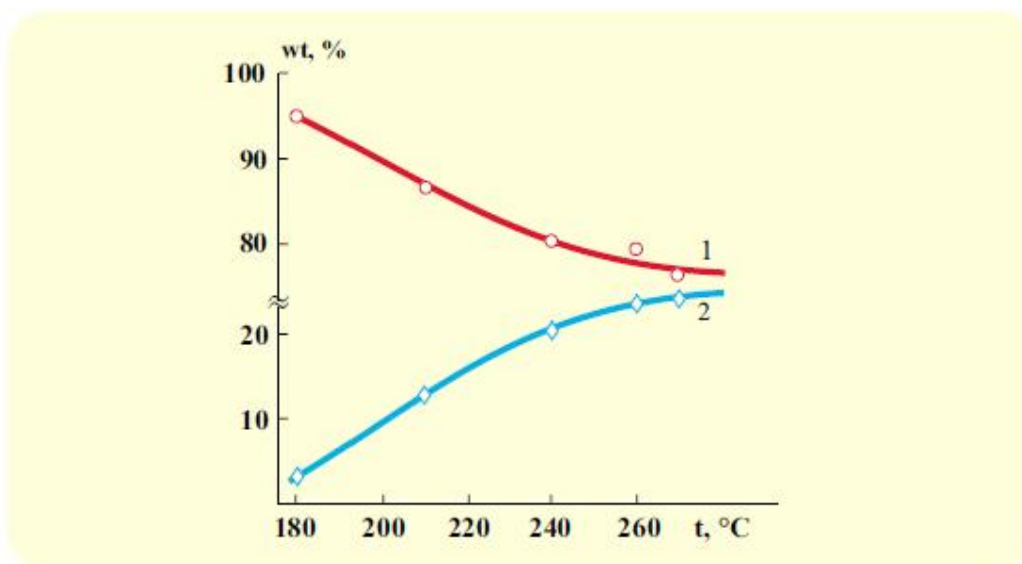
Рис. 2.10. Temperature dependences of consumption of H_2O_2
(1) in the catalase reaction and (2) in the hydroxylation reaction.

The experimental determinant value for the optimal hydroxylation conditions (240°C, C_3H_8 : H_2O_2 + 1:2 molar ratio, concentration of aqueous solution of H_2O_2 = 20 wt%, $V_{C_3H_8}$ = 0.3 1/h, $V_{H_2O_2}$ = 4.24 ml/h, and τ = 1.2 s) calculated by (4) is D ≈ 0.4. According to the scale of chemical interference [1] determinants, this value is in the region of chemical conjugation when the primary reaction of H_2O_2 decomposition induces the secondary one of C_3H_8 hydroxylation. It follows that the two synchronous reactions that occur in the system (the catalase and hydroxylation reactions) interact with each other [the coherence (find ≈ const) and induction (D ≈ 0.4) conditions are fulfilled] to produce a chemical interference picture in the form of synchronized and mutually related kinetic curves of the catalase and propane hydroxylation reactions.

2.5 Ethanol Oxidation

The dependences of the yields of acetaldehyde (CH_3CHO) and molecular oxygen (O_2) in the selective oxidation of ethanol in the presence of biomimetic catalysts on the contact time are shown in Fig. 2.11. At short contact times (up to τ = 2.3 s), the yield of acetaldehyde (the peroxidase reaction product) substantially increases and the catalase activity (the yield of O_2) decreases on all three catalysts.

The peroxidase activity decreased and the catalase activity, conversely, noticeably increased as τ grew larger. This makes it obvious that the kinetic curves of the catalase and peroxidase reactions are synchronized, which is doubtless evidence of the interaction between these two reactions and their coherent character. The kinetic curves of the catalase reaction show that H_2O_2 virtually fully decomposes to O_2 at small τ values. The observed yield of acetaldehyde in the oxidation of C_2H_5OH with hydrogen peroxide is then insignificant.

The consumption of hydrogen peroxide in each of the synchronized reactions of the oxidation of C_2H_5OH and the decomposition of H_2O_2 is shown in Fig. 2.12 as a function of contact time. We see that the total consumption of H_2O_2 in both reactions equals its initial amount. This leads us to

conclude that the total yield of reaction products corresponds to a constant H_2O_2 (actor) consumption, irrespective of the reaction conditions; that is, we have the following equality:

$$f_0 = f_1 + f_2 = const, \tag{9}$$

where f_0 is the initial amount of H_2O_2, and f_1 and f_2 are the amounts of H_2O_2 consumed in the catalase and peroxidase reactions, respectively.

Because of condition (9) of the coherence of chemical interference resulting from the interaction of two synchronous reactions, the rate of the catalase reaction (the decomposition of H_2O_2) decreases as the rate of the other (peroxidase) reaction, synchronized with the first one, increases, and vice versa. Such dependences are evidence that the two reactions (catalase and peroxidase) not only occur synchronously but also coherently interact with one another [1,5].

The contact time dependences of the yields of the catalase and peroxidase reaction products at various temperatures on the TPhPFe^{3+}OH/Al$_2$O$_3$ heterogeneous biomimetic catalyst are shown in Fig. 2.13. The kinetic curves of the yields of acetaldehyde at 120–160°C as a rule pass maxima at τ = 2.0 s. The yields decrease, most sharply at 120°C, as τ increases.

This property of the synchronous kinetic curves is probably related to the different temperature dependences of the catalytic activities of TPhPFe^{3+}OH/Al$_2$O$_3$ in the two synchronous reactions.
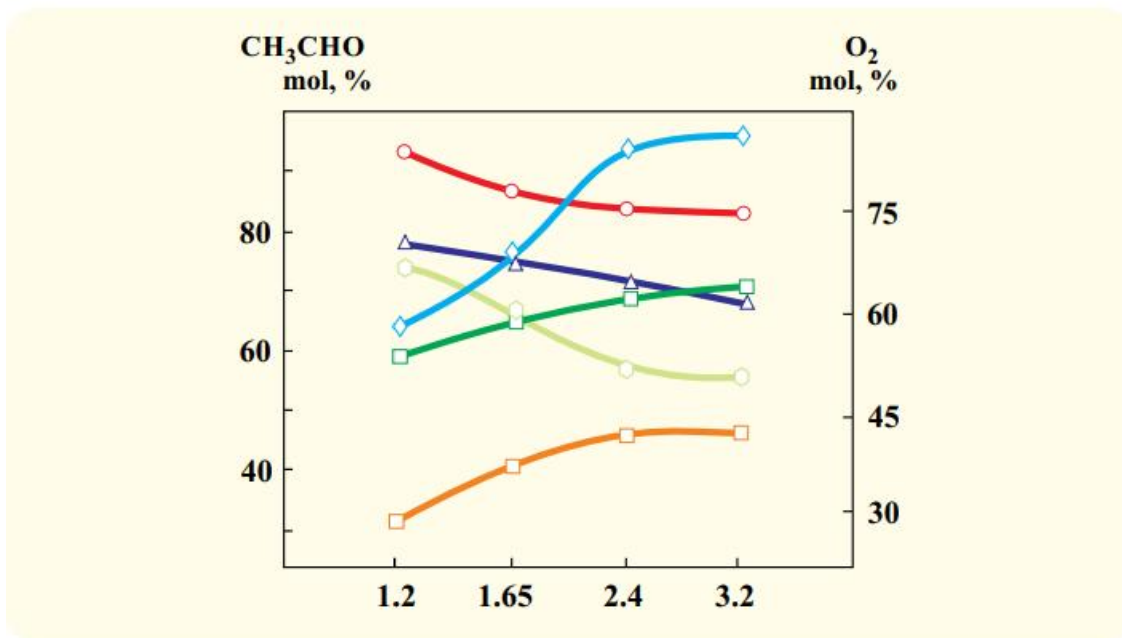
Fig. 2.11. Contact time τ dependences of the yields of the products of selective oxidation of C_2H_5OH [(1–3) CH_3CHO and (4–6) O_2] at 180°C and $c_{H_2O_2}$ =20 wt.% on (1, 4) TPhPFe^{3+}OH/Al$_2$O$_3$ (2, 5) PPFe^{3+}OH/Al$_2$O$_3$, and (3, 6) per-FTPhPFe^{3+}OH/Al$_2$O$_3$.
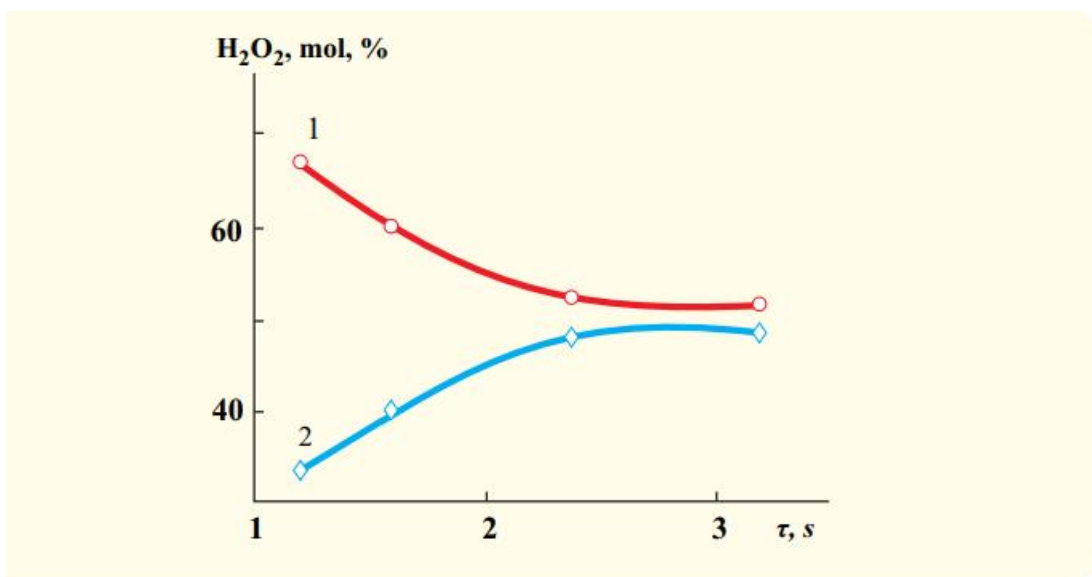
Fig. 2.12. Consumption of H_2O_2 in the (1) primary and (2) secondary reactions on $TPhPFe^{3+}OH/Al_2O_3$ at 180°C, $c_{H_2O_2}$ = 20 wt. %, and $C_2H_5OH{:}H_2O_2$ = 1:2.
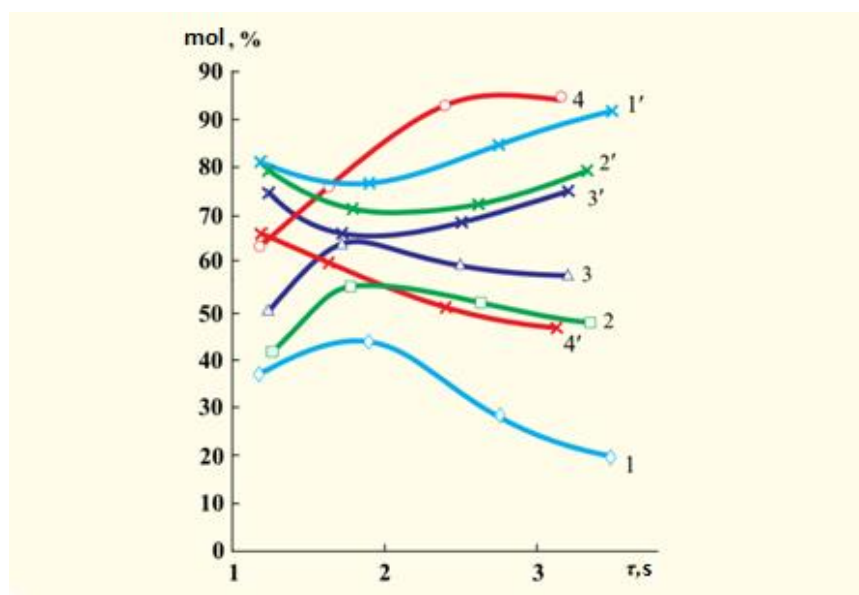
Fig. 2.13. Dependence of the yields of the reaction products (1–4 - CH_3CHO, 1' – 4' - O_2) on $TPhPFe^{3+}OH/Al_2O_3$ on the contact time at different temperatures: 1, 1' - 120, 2, 2' - 140, 3, 3' - 160, 4, 4' - 180°C

At high temperatures, its catalase activity is noticeably higher at contact times τ >2.0 s than the peroxidase activity, which synchronously decreases. The kinetic patterns of these two synchronous reactions are clearly seen at 180°C. The curve of the accumulation of acetaldehyde in the studied interval of contact times then contains no extrema but consistently decreases. Conversely, the curve of the catalase reaction goes upward. At higher temperatures, we observe the stabilization of the

yields of acetaldehyde and O_2. The high rate of the decomposition of H_2O_2 at these temperatures causes a sharp decrease in its concentration, which influences the rates of both synchronized reactions.

The kinetic conditions of the chemical interference manifestations are quantitatively estimated by the determinant equation (4).

The experimental determinant value calculated by this equation for the optimum conditions of the biomimetic oxidation of ethanol to acetaldehyde on TPhPFe^{3+}OH/Al$_2$O$_3$ (180°C, [H_2O_2] = 20 wt. % in water, molar ratio $C_2H_5OH:H_2O_2$=1:2, and τ = 1.6–3.2 s) is D = 0.30–0.50. According to the scale of the determinants of chemical interference [1,5], this value is in the region of chemical conjugation, when the primary reaction of the decomposition of H_2O_2 induces the secondary reaction of the oxidation of C_2H_5OH (the peroxidase reaction).

2.6 Oxidation of Cyclohexane

Most of the known oxidation processes of cyclohexane in the presence of various catalysts MnO, FeZSM, copper pyrophosphate, as well as in the biomimetic iron-porphyrin system FeP/O_2/Zn/AcOH/CH$_3$CN are carried out in the liquid phase. In contrast to liquid-phase oxidation processes, gas-phase processes on heterogeneous catalysts have their advantages: no special solvents are required; reaction products do not mix with catalysts, and this leads to the significant simplification of the process technology.

During the gas-phase oxidation of cyclohexane, as well as its mixtures (with methylcyclohexane and cyclohexanol), heterogeneous biomimetic catalysts – per-FTPhPFe(III)OH/Al$_2$O$_3$ and PPFe(III)OH/Al$_2$O$_3$ have been studied not only for their activity and selectivity, but also for the selectivity of their actions.

Experimental studies of the activity of per-FTPhPFe(III)OH/Al$_2$O$_3$ catalyst based on the temperature, concentration of hydrogen peroxide and contact time made it possible to obtain data indicative of its high activity in the process of cyclohexane monooxidation. Kinetic regularities of cyclohexane conversion over per-FTPhPFe(III)OH/Al$_2$O$_3$ biomimetic catalys as a function of temperature are presented in Fig. 2.14. As shown in the figure, oxidation of cyclohexane to cyclohexane and cyclohexanone at the temperature range of 150–180°C proceeds at the highest rate. With an increase in temperature, the yield of cyclohexene sharply increases and the yield of cyclohexadiene slightly increases, which is explained by the increase of the reaction rate of oxidative dehydrogenation of cyclohexane under these conditions (200–230°C). While the yield of cyclohexanol decreases with temperature, the yield of cyclohexanone at 180°C reaches its maximum (10.34% at 180°C).

It can be concluded from the nature of the kinetic curves 2 and 3 that the formation of cyclohexanone probably does not pass through the formation of an intermediate product of cyclohexanol. The temperature dependence of the kinetic curves shows that, starting from 200°C H_2O_2 decomposition into molecular oxygen stabilizes. This indicates that hydrogen peroxide in the system is completely consumed for carrying out of two interrelated reactions. This undoubtedly affects the processes of monooxidation and oxidative dehydrogenation of cyclohexane. This experimental fact indicates that the processes of monooxidation and oxidative dehydrogenation are interrelated with the reaction of H_2O_2 decomposition and proceed in a coherent with it manner. It is shown that such reaction system is effectively realized in a coherently synchronized regime. In this context, the kinetic data obtained in Fig. 2.14 are consistent with the theory and practice of coherently synchronized reactions [1,5] effectively realized in a coherently synchronized regime. In this context, the kinetic data obtained in Fig. 2.14 are consistent with the theory and practice of coherently synchronized reactions [1,5].

Since cyclohexanone (from Fig. 2.14) has been the dominant (target) product in our study, and its maximum yield (10%) has been observed at 180°C, the effect of contact time on the cyclohexane oxidation has been investigated at this temperature. Kinetic curves in Fig. 2.15 show that the increase in the contact time (x) in cyclohexane monooxidation reaction up to 10 seconds increases the yield of cyc-lohexanone (to 12.1%), and then the yield varies insignificantly. The rate of oxidative

dehydrogenation of cyclohexane to cyclohexene also increases, while the yield of cyclohexanone increases insignificantly. In this case, conversion of cyclohexane increases with increasing contact time. Kinetic regularities from Fig. 2.15 lead us to the conclusion that cyclohexanone is probably formed not from cyclohexanol. It should be noted that in the absence of cyclohexane, H_2O_2 at these contact times has been completely decomposed.
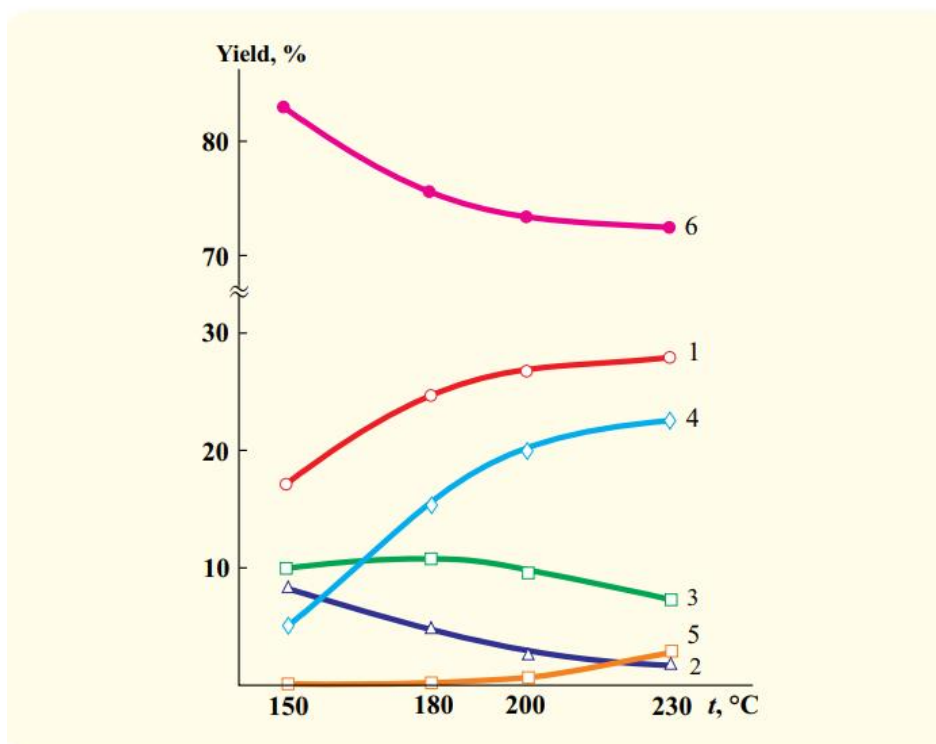
Fig. 2.14. The chromatogram of reaction products obtained during the analysis

on a chromium-mass spectrometer (retention time of cyclohexanone – 4.118 min.)

and mass spectrum of cyclohexanone.

The effect of the concentration of hydrogen peroxide in aqueous solution on monooxidation and oxidative dehydrogenation of cyclohexane is presented in Fig. 2.16. There is a rather interesting fact observed here: an increase in H_2O_2 concentration has an insignificant effect on cyclohexane conversion, while O_2 formation (catalase reaction), although very high in character, also varies insignificantly throughout the concentration range of H_2O_2. Nevertheless, the change in H_2O_2 concentration leads to significant decrease in the rate of cyclohexane oxidative dehydrogenation and significant increase in the yield of cyclohexanone. The kinetic curves indicating formation of monooxidation products which are cyclohexanone and cyclohexanol, show that the yield of cyclohexanone increases from 10 to 14%, while the yield of cyclohexanol passes through a maximum of 7.6%. The complex character of these kinetic curves in Figs. 2.14 and 2.15 does not give an unambiguous answer the key question: whether cyclohexanone is formed from cyclohexanol or not. In this regard, the reaction of cyclohexanol oxidation (97.52% of $C_6H_{11}OH$ in raw material) by hydrogen peroxide has been studied under identical conditions.

The kinetic curves in Fig. 2.17 show that peroxidase reaction of cyclohexanol, that is, the formation of cyclohexanone, is hardly observed. The dehydration of cyclohexanol to cyclohexene mainly proceeds here.
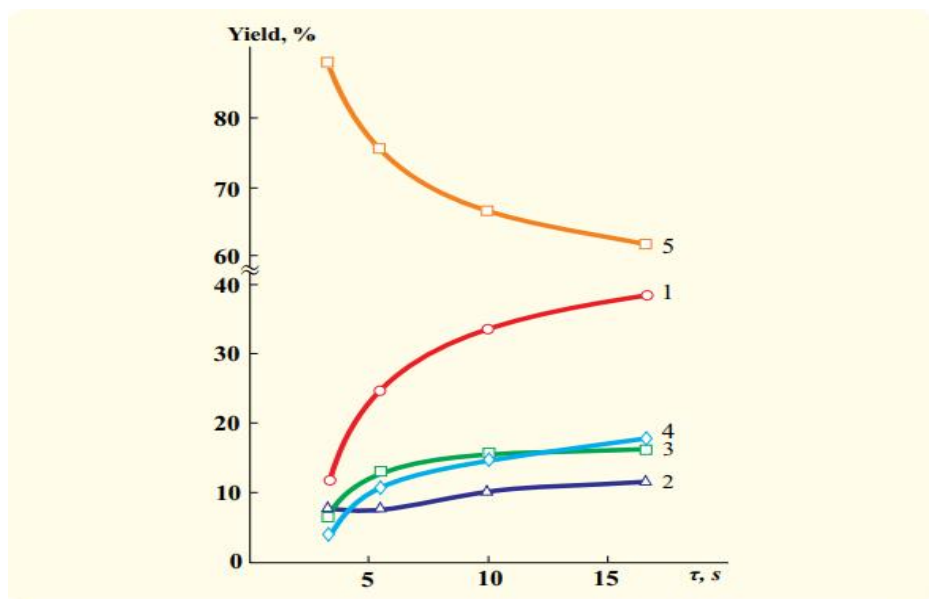
Fig. 2.15. Temperature dependence of the yields of cyclohexane oxidative conversion by hydrogen peroxide in a mixture with 6.25% of $C_6H_{11}OH$ and 2.53% of $CH_3C_6H_{11}$ on per-FTPhPFe(III)/Al_2O_3 biomimetic: $c_{H_2O_2}$= 25%, $V_{H_2O_2}$= 1.41 ml/h, $V_{C_6H_{12}}$ = 0.9 ml/h, C_6H_{12}: H_2O_2 = 1: 1.5; 1 – conversion of C_6H1_2; 2 – cyclohexanol; 3 – cyclohexanone; 4 – cyclohexene; 5 – cyclohexadiene; 6 – O_2.
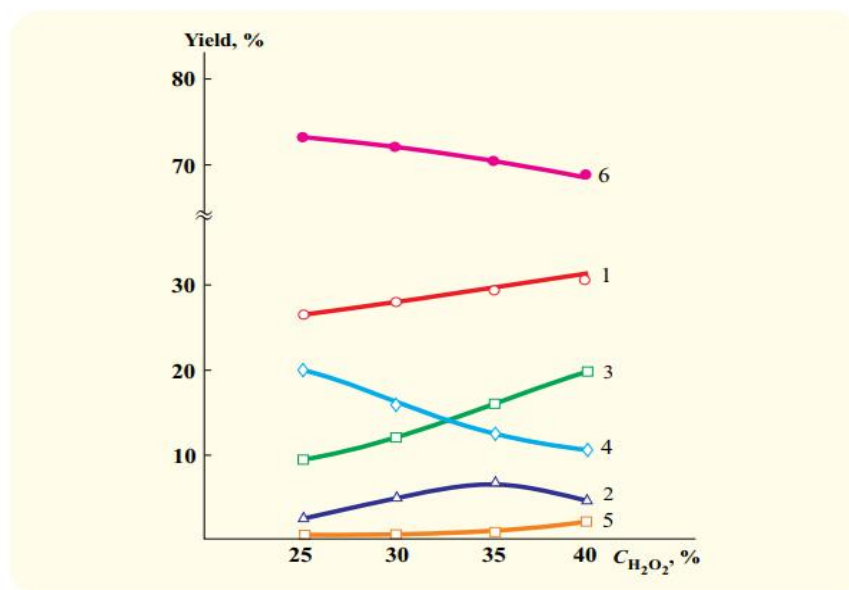
Fig. 2.16. Dependence of the yields of cyclohexane oxidation in a mixture of 6.25% of $C_6H_{11}OH$ and 2.53% of $CH_3C_6H_{11}$ on per-FTPhPFe(III)/Al_2O_3 biomimetic by hydrogen peroxide on contact time: $c_{H_2O_2}$ = 25%, t = 1800°C, C_6H_{12}: H_2O_2 = 1:1; 1 – conversion of C_6H_{12}; 2 – cyclohexanol; 3 – cyclohexanone; 4 – cyclohexene; 5 – cyclohexadiene; 6 – O_2.

It should be noted that an increase in temperature from 150°C to 230°C sharply increases the conversion of cyclohexanol towards the formation of cyclohexene. At the same time, the rate of molecular oxygen formation increases, which undoubtedly indicates that these processes proceed coherently through a common highly active intermediate compound (intermediate).

Thus, the kinetic data from Figs. 2.14 and 2.17 shed light on the mechanism of cyclohexanol and cyclohexene formation. Indeed, it can be seen from the kinetic data of Fig. 2.14 that at temperatures up to 150–180°C, the reaction of cyclohexane monooxidation proceeds, and when the temperature goes above 180°C the oxidative dehydrogenation of cyclohexane to cyclohexene (curve 4, Fig. 2.14) is accelerated, and respectively the yield of cyclohexanol and cyclohexanone decreases.
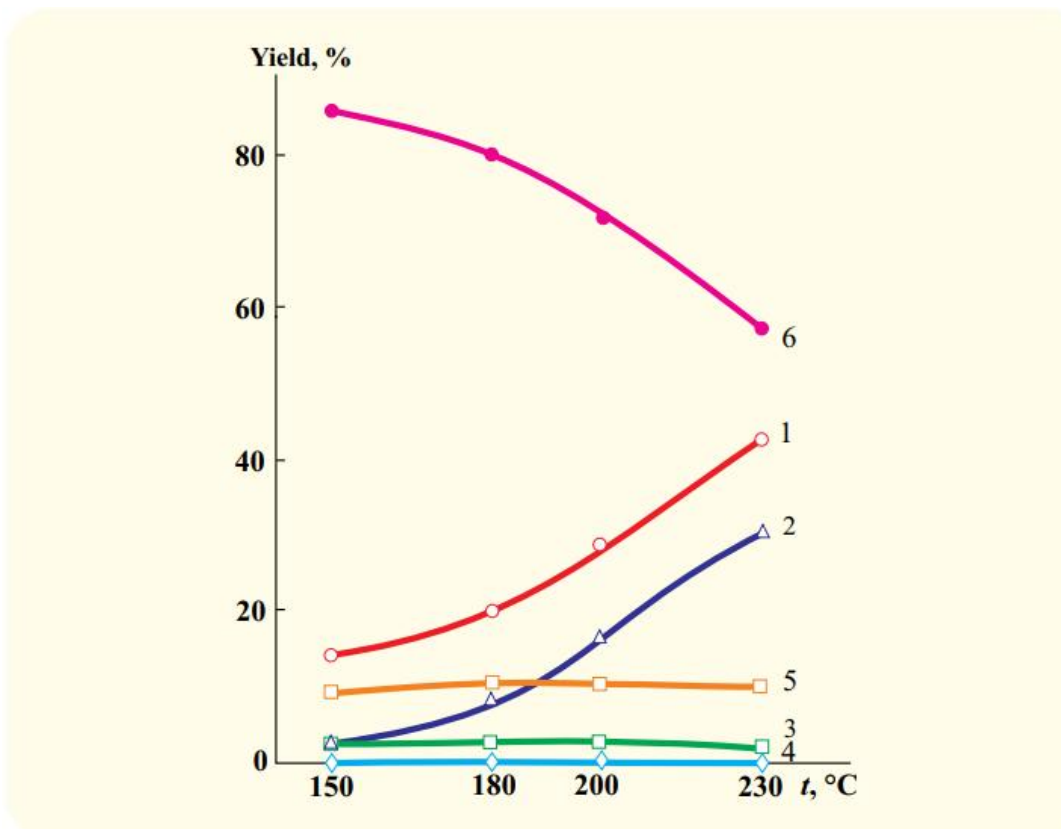
Fig. 2.17. Dependence of the yields of cyclohexane oxidation on per-FTPhPFe(III)/Al$_2$O$_3$ bioimitator on the concentration of H$_2$O$_2$ in aqueous solution:

$t = 200°C$, $V_{H_2O_2} = 1.41$ ml/h, $V_{C_6H_{11}OH} = 0.9$ mL/h;

1 – conversion; 2 – cyclohexanol; 3 – cyclohexanone; 4 – cyclohexene;

5 – cyclohexadiene; 6 – O$_2$.

A sharp increase in the yield of cyclohexene in parallel with a decrease in the yield of formed cyclohexanol indicates that at 230°C and at lower H$_2$O$_2$ concentrations in the reaction system, cyclohexanol is converted to cyclohexene. This conclusion is unambiguously confirmed by the experimental data of C$_6$H$_{11}$OH oxidation on the biomimetic catalyst at 200–230°C: cyclohexanol is completely dehydrated (Fig. 2.17) and high yields of cyclohexene are obtained (16–30%).

Thus, from the experimental data from Figs. 2.14–2.17 it can be concluded that the process of cyclohexene formation proceeds along a sequentially parallel mechanism, which can be represented as the following scheme:

(10)
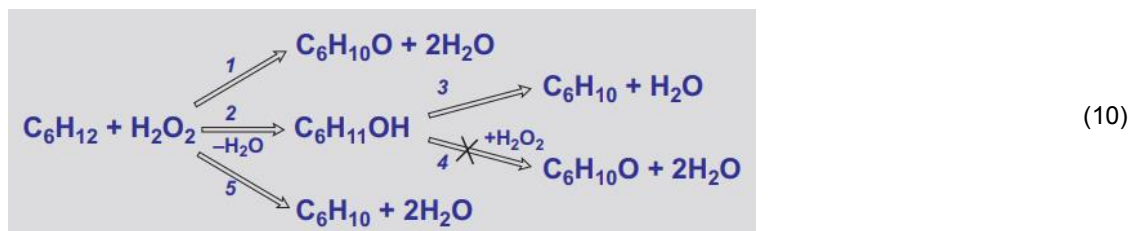
The reaction of cyclohexanone and cyclohexanol formation (reactions 1 and 2 from scheme 10) proceeds synchronously with the parallel-sequential reaction of cyclohexene formation.

Comparing the kinetic curves of cyclohexene formation in Figs. 2.14–2.17, it can be concluded that at a temperature above 180°C and at the lowest concentration of H_2O_2, the major part of cyclohexene is formed by the oxidative dehydrogenation of cyclohexane by reaction 5 (from scheme 10). Of course, this does not exclude the possibility of cyclohexene formation by consecutive reactions 2 and 3 (from scheme 10).

The next stage of our research has been the study of biomimetic catalytic system with regard to the selective nature of its influence when mixtures of cyclohexane with some of its derivatives are used. The results of studies using raw materials with 88.85% of C_6H_{12}, 6.25% of $C6H_{11}OH$ and 2.53% of $CH_3C_6H_{11}$ have demonstrated that during the oxidation process, cyclohexane is mainly being converted, and the amount of methylcyclohexane in the raw material remains practically unchanged.

In order to define the selective effect of the iron- phosphorene-containing biomimetic catalysts we have used in the oxidation of complex mixtures, an artificially prepared mixture containing 45.4% of C_6H_{12}, 38.64% of $CH_3C_6H_{11}$, and 1.91% of $C_6H_{11}OH$ has been used as the raw material. The results of the study of oxidation of this mixture by 20% hydrogen peroxide at different feed rates and different temperatures on PPFe(III)/Al$_2$O$_3$ biomimetic are shown in Table 2.1. According to the data in Table 2.1, there is an unequivocal conclusion about selective effect of the catalytic biomimetic on the oxidation of cyclohexane in the mixture with significant amount of methylcyclohexane (38.6%).

Table 2.1. The results of cyclohexane oxidation in the mixture of PPFe(III)/Al$_2$O$_3$ biomimetic by hydrogen peroxide

t, °C	Composition of raw material				Reaction products						α, %	[O$_2$], %
	C_6H_{12}	C_6H_{11} CH_3	$C_6H_{11}O$ H	C_6H_{10} $(CH_3)_2$	C_6H_{12}	C_6H_{11} CH_3	$C_6H_{11}O$ H	$C_6H_{11}O$	C_6H_{10}	C_6H_{10} $(CH_3)_2$		
150	45.439	38.638	1.913	5.479	37.1	38.928	0.641	3.445	6.256	6.771	8.34	91
180	45.439	38.638	1.913	5.479	33.19	39.31	1.848	4.239	8.073	7.078	12.2	88
200	45.439	38.638	1.913	5.479	29.34	36.579	2.793	5.715	9.5	7.165	16.0	84
220	45.439	38.638	1.913	5.479	24.85	38.63	2.5	7.5	12.5	6.7	20.5	79

Note: $C_{H_2O_2}$ = 20%, $V_{H_2O_2}$ = 1.41 ml/h, $V_{C_6H_{11}OH}$ = 0.9 ml/h; α – conversion, [O$_2$] – O$_2$ yield in the catalase reaction.

Thus, the investigated catalytic biomimetic has been not just highly selective, but also selective towards the oxidizable substrate. As a rule, this is typical of only monooxygenase enzymes.

Coherently synchronized reactions of cyclohexane monooxidation by hydrogen peroxide are described by the following generalized scheme:

(11)
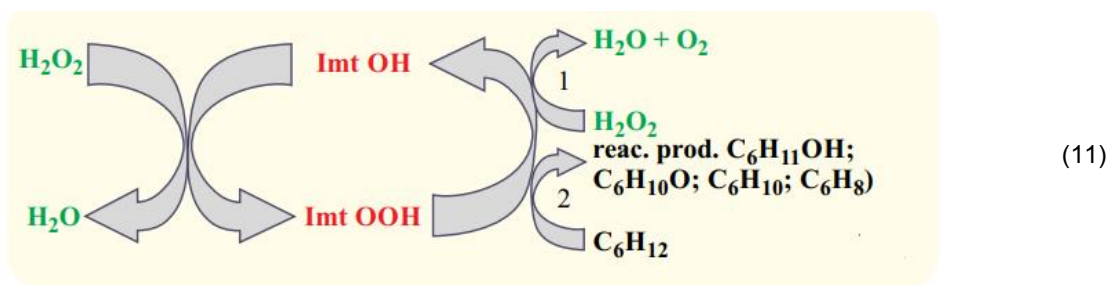
It follows from this scheme that the primary H_2O_2 decomposition reaction forms highly active hydroperoxide active center, which interacts with cyclohexane by forming the desired products (secondary reactions), according to the following most probable mechanism (12).

(12)
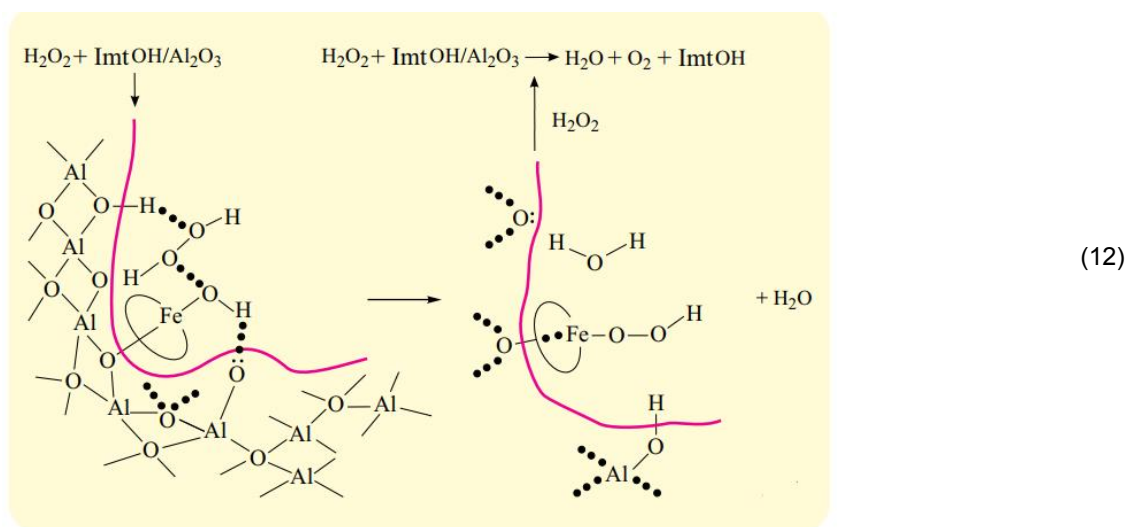
where, $ImtOH/Al_2O_3$ is a catalytic biomimic (simulator); $ImtOOH/Al_2O_3$ is an intermediate; $+$and $\cdots$ are, respectively, the gap and the formation of links. The scheme (12) shows the principle of constructing of $ImtOOH/Al_2O_3$ complex on per-FTPhPFe^{3+}OH/Al_2O_3 biomimic, which is analogous to the formation of the Chance complex (PPFe^{3+}OOH) under the effect of the catalase enzyme [1,5]. In our case Al_2O_3 is used as the matrix of acid-base nature.

The above monooxygenase reactions are coherently related to the primary H_2O_2 decomposition reaction and this factor is measured using the determinant equation:

$$D = v \left(\frac{f_1}{f_{Acc}} + \frac{f_2}{f_{Acc}} \right)^{-1} ,$$

where, f_1 is amount of the actor consumed by H_2O_2 in the catalase reaction; f_2 is amount of the actor consumed by H_2O_2 in the monooxygenase reaction and in the oxidative dehydrogenation reaction: $f_2 = f_2' + f_2''$, f_2' is amount of H_2O_2 consumed in the monooxygenase reaction, f_2'' is amount of H_2O_2 consumed in the oxidative dehydrogenation reaction; f_{acc} is the consumption of substrate-acceptor (cyclohexane); v is stoichiometric coefficient of the actor.

Calculated values of the determinant, as well as data on the coherence ratio are given in Table 2.2 according to equation:

$$f^0_{H_2O_2} = f^1_{1,H_2O_2} + f^1_{2,H_2O_2} = f^2_{1,H_2O_2} + f^2_{2,H_2O_2} = const,$$

which unambiguously indicates that considered reactions are coherently synchronized.

$$f^0_{H_2O_2} = f^1_{1,H_2O_2} + f^1_{2,H_2O_2} + f^1_{2',H_2O_2} =$$

$$= f^2_{1,H_2O_2} + f^2_{2,H_2O_2} + f^2_{2',H_2O_2} = \ldots = const,$$

$$0,0072 = 0,0057 + 0,0015 =$$

$$= 0,0052 + 0,0016 + 0,0004 = \ldots = const.$$

Thus, the coherent synchronization of these reactions (values of D < 1) [1,5] allows us to consciously control the rates and direction of these complex target reactions. So, if we, for example, mainly need to obtain products of cyclohexanol and cyclohexanone monooxidation, knowing that they correspond to low determinant values, then by keeping it low and, accordingly, manipulating reaction conditions, the process will be effectively directed toward monooxidation. Thus, using the D factor, we determine the best conditions for the production of cyclohexanol and cyclohexanone. According to the data in Table 2.2, the conditions are as fol-D = 0.28: t = 150°C, τ = 5.92 s, molar C_6H_{12}: H_2O_2 = 1:1, the yield ofmonooxidation products is 18.46%. According to the Table 2 for the oxidative dehydrogenation of cyclohexane to cyclohexene, under the studied conditions, the value of the determinant D = 0.35 corresponds to the most efficient course of this reaction. By manipulating the D factor value the process can be directed both toward monooxidation and toward oxidative dehydrogenation. In addition, the D factor makes it possible to determine the potential for obtaining the best yield of a given product by the target – secondary reaction. For example, if we want to intensify the process of oxidative dehydrogenation by increasing the D value to 0.6, then it is sufficient to insert this value into the determinant equation and determine the ratio of the initial reagents and H_2O_2 consumption in the secondary and primary reactions. This will give us the conditions under which it is possible to achieve higher yields of the desired product: cyclohexene.

Table 2.2. Determinants of the reaction of monooxidation and oxidative dehydrogenation of cyclohexane and the amount of H_2O_2 consumed in these reactions

№	t, °C	τ, c	$N^0_{C_6H_{12}}$, mole/h	$f^0_{H_2O_2}$, mole/h	α, %	$C_6H_{10}O+C_6H_{11}OH$, %	$C_6H_{10}+C_6H_8$, %	f_1, mole/h	$\dfrac{f_2}{f_2'}$, mole/h C	f_{acc}, mole/h	D
1	130	6.21	0.0083	0.0072	17.242	17.242	0	0.0057	0.0015 0	0.0015	0.21
2	150	5.92	0.0083	0.0072	23.158	18.458	4.7	0.0052	0.0016 0.0004	0.0020	0.28
3	180	5.52	0.0083	0.0072	26.05	17.490	8.56	0.0050	0.0015 0.0007	0.0022	0.31
4	200	5.29	0.0083	0.0072	27.6	14.628	12.972	0.0049	0.0012 0.0011	0.0023	0.32
5	230	4.97	0.0083	0.0072	29.84	19.141	20.7	0.0047	0.0008 0.0017	0.0025	0.35

Note: $C_{H_2O_2}$ = 25%, $V_{H_2O_2}$ = 0.9 ml/h, $V_{C_6H_{12}}$ = 0.9 ml/h; α – conversion C_6H_{12}, molar ratio C_6H_{12} : H_2O_2 = 1:1.

The solution of the determinant equation in the framework of the kinetic equations of the rates of two coherently synchronized reactions with determination of constants and activation energies will make it possible to develop a kinetic model of cyclohexane conversion process based on the general scheme.
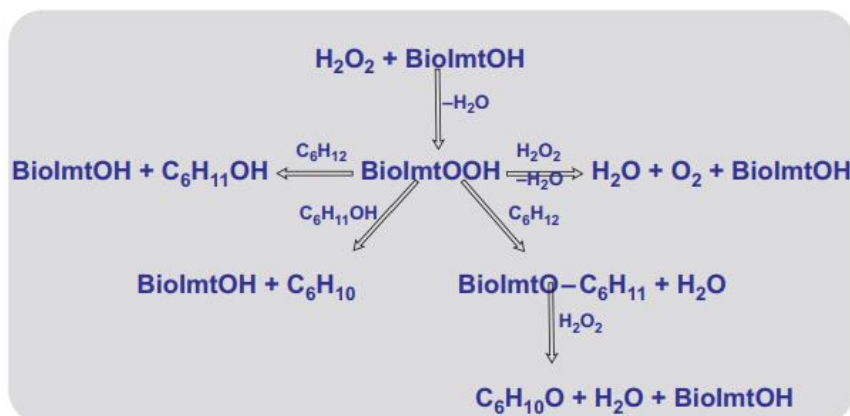
In conclusion, it should be noted that the determinant equation for a chemical system with coherently synchronized (primary and two secondary (target)) reactions adequately describes the experimental results.

The selective effect of iron-porphyrin-containing biomimetic catalyst on cyclohexane during the oxidation of cyclohexane in the mixture with its derivatives has also been determined by experimental study.
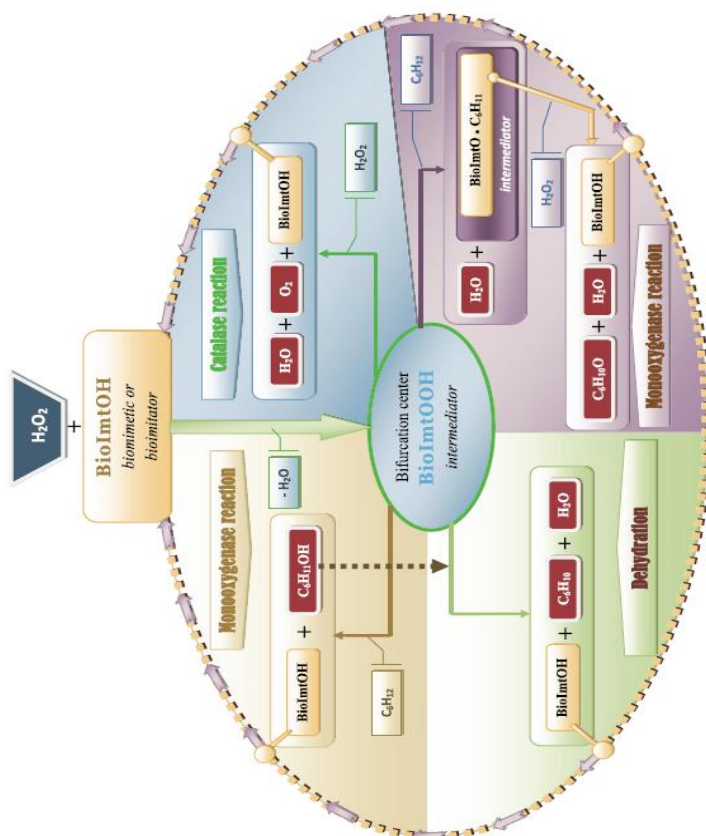
Infographics of the coherently synchronized monooxygenase reaction of cyclohexane with hydrogen peroxide
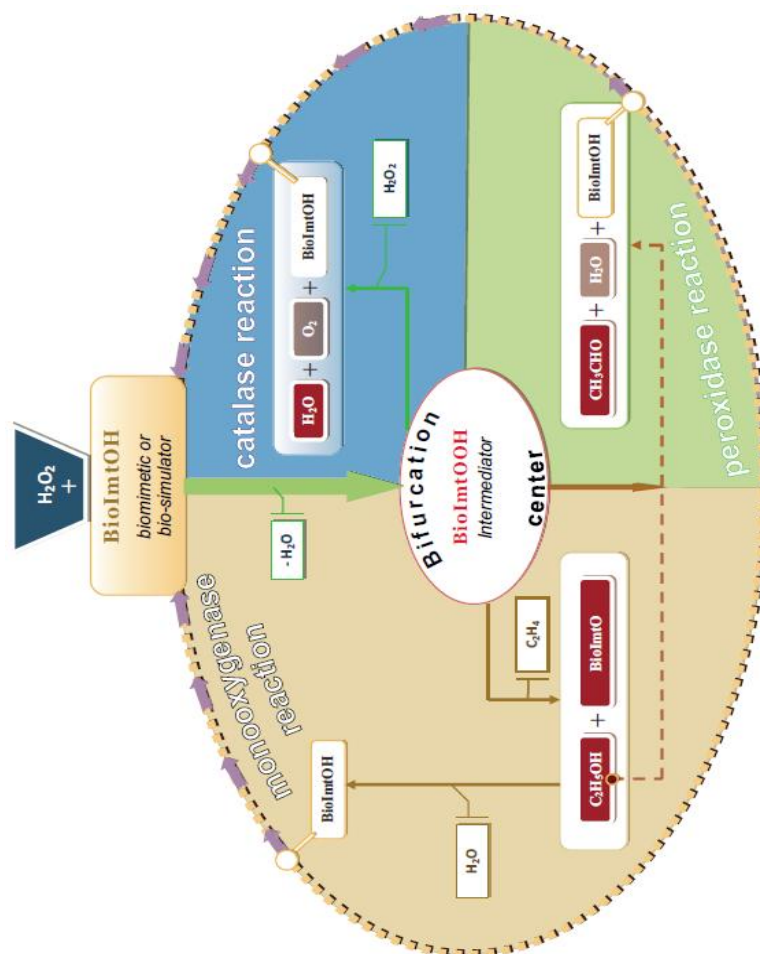
Biomimetic catalytic monooxidation of ethylene to ethyl alcohol and acetaldehyde by hydrogen peroxide

3. CHEMICAL INTERFERENCE-INTERVENTION OF ONE REACTION INTO ANOTHER

Simple and complex stoichiometric reactions with no interference are at the central position of the scheme (5) with D = v . Such complex reactions include parallel, sequential and parallel-sequential reactions. To the left of this position, when D < v, there are conjugate reactions that are part of coherently synchronized reactions.

With chemical induction, the secondary conjugate reaction can never be monomolecular. This is explained by the fact that the intermediate product of the primary reaction, being a reagent of the secondary reaction, is consumed in it, which naturally leads to a gross equation with participation of more than one component. The majority of biochemical oxidation processes is conjugate or coherently synchronized catalytic (enzymatic) reactions. Therefore, it is very important to distinguish a catalyst from an inductor, because any error in this matter may lead to an incorrect interpretation of the chemical mechanism of reactions occurring in the biological system. For example, a catalyst of redox reactions is often taken as an inductor.

Is there a fundamental difference between conjugate and coherent-synchronized reactions? In fact, they are described by almost the same chemical equations, but with one distinctive feature. This feature is clearly shown in Fig. 1. The conjugacy of synchronous reactions in this scheme is shown

using an arrow indicating unilateral influence of the primary reaction on the secondary one. While in coherent-synchronized reactions, both reactions affect each other, which indicate the presence of feedback. It is the bilateral nature of interaction of synchronous reactions that is responsible for the interference pattern—the primary reaction accelerates the secondary one, which in turn slows the former one down. This coherent and dynamic chemical interference is uniquely described by consistent kinetic patterns of both reactions. The term inductor retains its universal meaning in both cases. Essentially, conjugate reactions are a reflection of coherently synchronized reactions in the forward direction and therefore they can be considered a as a special case of coherently synchronized reactions with a simple mathematical apparatus (3) and (4).

It should be emphasized once again that an actor in the conjugate reactions is consumed as much as it participates at the stage of formation of an inducing intermediate (bifurcation center) in the primary reaction, which is distributed to the formation of final products of the primary and secondary reactions (bifurcation occurs) (Fig. 2).

(13)
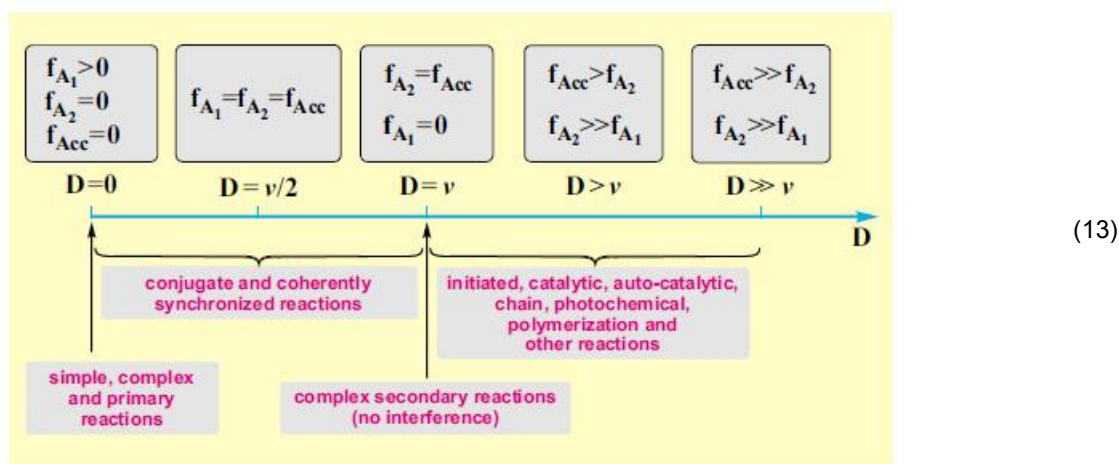
The scale of the determinant of chemical interference

$D = 0 \div v$ is the area of chemical conjugation;

$D > v$ is the area of other interrelated interfering reactions.

However, there is an unsuccessful attempt in the recent article [8] to prove that in the system of conjugate reactions elementary stages are actually interfaced. On the basis of this position, they reject one of the basic postulates of chemical kinetics about independence of elementary reactions.

According to Ostwald and Shilov [9], only the complex reactions can conjugate, and not the elementary stages that constitute mechanisms of the primary and secondary reactions. In the primary reaction, due to the elementary stage, a highly active intermediate particle is generated into the system, and then consumed through two channels (the primary and secondary reactions). This elementary stage must necessarily be present in the stage mechanisms of both gross reactions. Hence, only complex reactions can have common highly active intermediate particles (intermediates) as centers of bifurcation; therefore, they can be conjugated according to Shilov, and not their elementary stages, as stated in [13].

A similar erroneous statement in [11] was expressed by Rakovsky A.V.: "... the phenomenon of the transfer of reactivity from one reaction to another is called chemical induction ... Obviously; in this case we are dealing with deviation from the principle of independence of reactions". However, in the textbook by Emanuel N.M. and Knorre D.G., p. 234 [14], the following idea is clearly and precisely expressed: "An elementary reaction cannot be induced by another reaction. This follows from the regulation on the independence of elementary reactions, according to which rate constants of an

elementary reaction do not depend on whether other chemical processes occur simultaneously in the same system".

A common elementary stage in conjugate reactions cannot perform the function of a bifurcation center, only a highly active intermediate particle can.

Therefore, this is another reason why the statement about the conjugation of elementary stages, being a distortion of the concept of chemical conjugation itself, is not permissible.

The authors of [8] on p. 2016 gave the scheme and added the following "in the absence of the stage of product P2 formation from X, i.e. the primary reaction, an essence of the CP phenomenon with chemical induction is preserved". The reason why this is a completely erroneous statement is the following: if a highly active intermediate X is not a bifurcation center, i.e. subsequently it forms only the products of the secondary reaction. Thus, in the absence of the end products of the primary reaction a stoichiometric complex reaction with the determinant $D = v$ is observed in the reaction system. Only the presence of the final products of the primary reaction allows us to consider them as conjugate and their determinants are always $D < v$. All this is described in sufficient detail in the monographs [1,4] [5]. At the time of writing of Shilov's book in 1905 [9], the nature of highly active intermediate compounds (free radicals, active complex compounds, forms of ions, etc.) were not known. Stable intermediate compounds of sequential reactions were often mistaken for intermediates. The reaction of water oxidation by oxygen to hydrogen peroxide (the secondary reaction), allegedly predicted by Shilov, was cited in [8], as an example. "Since the oxidation of H_2O to H_2O_2 cannot proceed arbitrarily and is accompanied by energy absorption, then, according to this theory, the H_2O_2 formation itself already represents the case of two conjugate processes with simultaneous flow where antozone is an intermediate product" [9]:

$$X + O_2 = XO + O' \text{ primary reaction} \tag{14}$$

Antozone

$$H_2O + O = H_2O_2 \quad \text{secondary reaction} \tag{15}$$

Reaction (16) and (17) are essentially sequential elementary reactions and antozone is not a common intermediate particle (intermediate) and therefore these reactions cannot be conjugated in the conventional sense.

Further, according to Shilov [9], "Traube in 1884 received a patent for the production of H_2O_2 by introducing water into the flame, formed by burning CO, H_2, water gas, etc."

"... At the temperature below $900°C$, H_2O_2 in equilibrium exists in trace amounts."

The scheme in [8] is absolutely incorrectly taken as the basis of their understanding of the theory of conjugate reactions, which is illustrated by the following statement: "A classic example of a process with chemical induction is the oxidation of benzene to phenol, which proceeds in conjunction with the oxidation of Fe^{2+} by hydrogen peroxide (Fenton's system)".

This reaction system is classical and is considered in many textbooks and monographs as a vivid example of conjugation of two gross reactions—oxidation of Fe^{2+} by hydrogen peroxide (Fenton reaction) and oxidation of benzene to phenol by hydrogen peroxide.

Fenton reaction: Ions of iron (II) in the liquid phase are oxidized by hydrogen peroxide to Fe (III) ions, which are later converted back to iron (II) affected by hydrogen peroxide [12]:

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + \dot{O}H + OH^- \tag{16}$$

$$Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + \dot{O}OH + H^+ \tag{17}$$

It follows from the reactions (8) and (9) that Fe^{2+} and Fe^{3+} ions are the catalysts for the decomposition of H_2O_2 with the formation of water and O_2:

$$OH + HO_2^\cdot \rightarrow H_2O + O_2$$

$$\dot{O}H + H_2O_2 \rightarrow H_2O + HO_2^\cdot$$

$$Fe^{3+} + HO_2^\cdot \rightarrow Fe^{2+} + H^+ + O_2$$
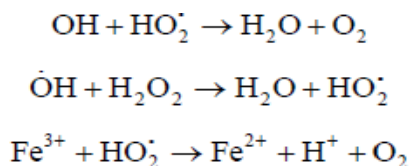
Thus, Fenton's reagent generates hydroxyl radicals into the system. The Fe^{2+} ion is a catalyst for this reaction and cannot perform useful work in the system to induce and accelerate another secondary reaction associated with it (Shilov p. 10 [9]).

The function of highly active intermediate substance is performed by $\dot{O}H$ radical—a product of the primary reaction of H_2O_2 catalytic decomposition (see reaction 1). In this respect, the Fenton reaction is considered in the monograph (pp. 243-254 [4]) as a reaction inducing the secondary reaction.

Essentially, Fenton's reagent in the system of conjugate reactions is associated with the formation of $\dot{O}H$ radicals in the reaction of H_2O_2 decomposition:

$$H_2O_2 + H_2O_2 \xrightarrow{\ Fe^{2+}\ } 2H_2O + O_2 \tag{18}$$

The first elementary reaction of a complex reaction (10) is a stage (18), where Fe^{2+} catalyst is oxidized to Fe^{3+}, and then Fe^{3+} is reduced (19) to Fe^{2+}, thereby closing the catalytic cycle. Naturally, this catalyst, like any other, cannot have an inducing effect (to be a power source for a secondary reaction). In addition, the elementary reaction (18) cannot cause and accelerate another elementary reaction of the secondary reaction, since this contradicts the basic pri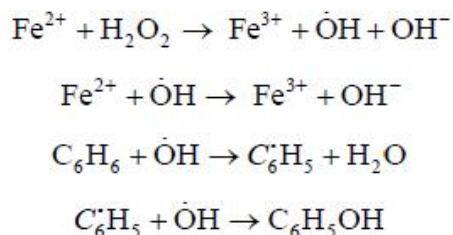nciple of kinetics— the elementary reactions proceed independently from each other; otherwise, the rate constant of elementary reactions would always be a variable value.

Shilov (pp. 10-12 [9]) states: "... since the catalyst does not change during the process, it cannot serve as a power source and, therefore, does not change the driving force of the reaction. The catalyst, not being a power source, causes only those processes that can proceed arbitrarily at least with very little speed". Thus, the catalyst can never be taken as an active intermediate substance. According to Shilov, "A general task in studying conjugate reactions is determining the nature of intermediate products that serve as a link between the primary and secondary reactions (p. 16 [9])".

Let us consider an oxidation reaction of benzene with hydrogen peroxide in the Fenton system as a classic case. In the textbook on kinetics [14] as well as in [8], during the oxidation of benzene to phenol, in the presence of Fe^{2+} ions (Fenton's reagent), oxidation of benzene to phenol and the oxidation of Fe^{2+} by hydrogen peroxide are considered as conjugating reactions:

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + \dot{O}H + OH^-$$

$$Fe^{2+} + \dot{O}H \rightarrow Fe^{3+} + OH^-$$

$$C_6H_6 + \dot{O}H \rightarrow C_6^\cdot H_5 + H_2O$$

$$C_6^\cdot H_5 + \dot{O}H \rightarrow C_6H_5OH$$

It follows from this mechanism, that the oxidation of Fe^{2+} and C_6H_6 is carried out with the participation of a common intermediate—$\dot{O}H$ free radicals. $\dot{O}H$ free radical is a common intermediate, which is involved not only in this reaction, but also in many other oxidation reactions. Fe^{2+} ion is usually a catalyst for the decomposition of H_2O_2 and in the Fenton system it cannot perform useful work for the

secondary reaction. Therefore, the oxidation of Fe^{2+} cannot be considered as a conjugating factor in the oxidation of benzene: a flow of the reaction of H_2O_2 decomposition to $\dot{O}H$ with the participation of the Fe2+ ion as a catalyst (Fenton Reagent) is necessary. The decomposition of H_2O_2 under the action of the catalyst Fe^{2+} to H_2O and O_2 (primary reaction) is conjugated with the secondary oxidation reaction of benzene with hydrogen peroxide. In this case, the free radical $\dot{O}H$ is a carrier of the inducing action of H_2O_2 (inductor) on the secondary reaction:

$$\underset{\text{actor}}{H_2O_2} + \underset{\text{inductor}}{H_2O_2} \xrightarrow{Fe^{2+}} 2H_2O + O_2$$

$$\underset{\text{actor}}{H_2O_2} + \underset{\text{acceptor}}{Acc} = \underset{\text{final product}}{FP}$$
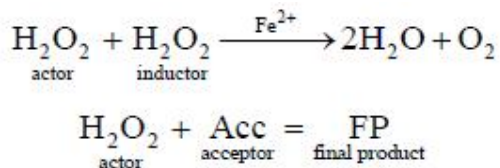
This scheme "describes a process of the chemical conjugation in the oxidation reactions with hydrogen peroxide not only in the gas phase, but also in the liquid phase" [1-6] as well as in the presence of various catalysts in both conjugate reactions. Summing up these arguments, we see the fallacy of the statement in [8] that the oxidation reaction of benzene to phenol proceeds in conjunction with the oxidation of Fe^{2+} with hydrogen peroxide. Moreover, the catalyst can be neither an actor nor an inductor, since the inductor and the actor should be consumed during the reaction [9].

It is noted in [8] that the actor consumption in the conjugate reactions is determined by the stoichiometry and the number of products of the primary and secondary reactions, i.e. the material balance of the process, and not by how much of it is consumed in the primary reaction during the formation of the key intermediate X (p. 47 [4]). There is no denying the fact that the material balance of the process determines the flow rate of the actor and the inductor. Moreover, guided by this in [1-6], the conjugate reactions are considered in general form according to the scheme (2).

A role of intermediate X, which is common for conjugate reactions, is very clearly revealed in this scheme. The inductor is consumed in an amount that ensures consumption of A in both reactions. It clearly follows from the scheme (2): "how much actor is consumed in the primary reaction vA + In, which is the initial stage of X formation—the bifurcation center, where reaction 1 is responsible for the formation of the final products of the primary reaction and reaction 2 for the formation of the secondary reaction products". In other words, the scheme (2) demonstrates a simple regulation that the actor is consumed exactly as much as it is necessary for the formation of X in primary reaction and this absolutely does not contradict the material balance. There is the following phrase in [8] "the reaction with H_2O_2 hinders the development of the chain process of H_2O_2 decomposition" that I was credited with, which is not found in the monograph [4]. Surprisingly, this phrase is given in brackets, thus it is difficult to figure out what is meant by the authors. Moreover, the use of dubious approaches for the approval of their own ideas leads authors [8] to the absurd. For example, "The final equation

$$2H_2O_2 + 2Fe^{2+} + C_6H_6 = C_6H_5OH + 2Fe(OH)^{2+} + H_2O$$
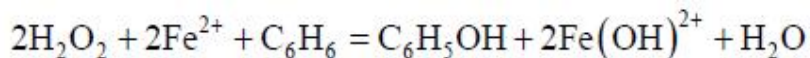
which in fact, is the result of the addition of the twice-repeated first-stage reaction of Fenton and two stages involving benzene" is further stated in [9]. This final reaction includes a Fe^{2+} catalyst as a starting reagent. It follows that performing a useful work (free energy) it contributes to the formation of the final product of the secondary reaction—phenol. We have already discussed above that the catalyst cannot in principle be a power source and therefore the inclusion of the catalytic stage in the final gross equation of the secondary reaction is not correct.

The authors [8] consider that: "A conjugation of elementary stages through common intermediates as a universal phenomenon. Presence of common intermediates that ensure mutual influence and interconnection of rates and chemical affinity of successive adjacent stages of the mechanism, as well as the interrelation of the reactions of formation of various products (through different routes), should be called kinetic conjugation".

Concerning the validity of such statement, Shilov gives a rigorous explanation on pp. 1-2 [9]: "... the concept of conjugate processes is opposite to the well-known principle of coexistence of reactions, although it is possible that conjugation of reactions does not contradict this basic law of chemical dynamics, since the principle of coexistence means elementary reactions flowing without intermediate phases and in accordance with empirical equations; conjugation of reactions is possible only with complex processes that represent a sequence of individual reactions and lead to the formation of intermediate products".

We have already expressed our attitude towards the term "conjugation of elementary reactions", and as for the concept of "kinetic conjugation" proposed in [8], this expression in the context of the theory of conjugate reactions is meaningless.

The statement on p. 278 [8]: "Although a phenomenon of the kinetic conjugation in case of complex reactions is universal, only the stages having a common intermediate and included in a sequential chain of reactions have a positive effect on each other. The existence of a common intermediate in parallel reactions ...". The concept of parallel reactions ultimately eliminates the presence of a common intermediate, and the presence of the latter is characteristic only of conjugate reactions.

Complex reactions can be in conjugation in the case when they have a common source substance-actor. However, this is a necessary but not sufficient condition. A sufficient condition is the presence of highly active intermediate common for these reactions. The combination of these two conditions fundamentally distinguishes conjugate processes from parallel and other complex reactions that have a common source substance.

Another expression from the same page: "The basic reaction (III) can proceed in parallel with the reaction (XVII) through a common intermediate". Parallel reactions and the general intermediate reflect a continuous confusion that underlies the so-called "Kinetic conjugation". There is a simple and clear trivial expression "kinetics of conjugate reactions" which does not allow such distortions in kinetic terminology.

"The sequential reactions (stages) mutually influence the flow rate of each other due to changes in the concentration of the common intermediate" (p. 281 [8]). Mutual influence of the successive stages through the "common intermediate" contradicts the concept of sequential reactions. The intermediate formed in the first elementary stage, as its final product, is the starting point for the second stage, etc. and their course obeys the principle of independence of the course of elementary stages.

The intermediate common for two conjugate reactions undoubtedly changes the mechanism of the secondary reaction and, naturally, this circumstance affects the kinetics and thermodynamics of the conjugated process [1-6].

Concerning the following expression on p. 281 [8] "... thermodynamic conjugation occurs in the case of simple parallel reactions", it can be stated that simple reactions take place in one elementary stage, and for this reason they cannot be conjugate, including simple parallel ones.

It is also stated on page 282 [8] that "... the kinetic conjugation of the stages is a characteristic feature of all complex reactions". According to the authors all known complex chemical reactions are conjugate, and their notion of "kinetic conjugation" leads to this false conclusion.

Their reasoning indicates that "The main feature of unbranched and branched chain processes is the kinetic conjugation of two or more routes ...", which leads to a complete confusion.

It is given on page 286 [8] that "... the flow of the parallel reactions, which do not have common with the main process reagents (parallel reactions always have one common reagent) and intermediates, does not make the endoergic process thermodynamically possible. It was shown above that interrelation of rates takes place only with the presence of common intermediates in sequential and parallel- sequential reactions (i.e. , with the presence of the kinetic conjugation)...".

We have already mentioned above that parallel, sequential, parallel-sequential, as well as conjugate reactions are completely independent kinetic concepts. They are considered within the framework of complex gross reactions and bringing them into one concept of "kinetic conjugation" is scientifically meaningless.

The authors [8] analyze another phrase from my book [1]: "For example, the first characteristic feature of conjugate reactions according to Nagiev ([4] p. 38) is as follows: '... the decrease in free energy in the primary reaction fully covers the increase in free energy in the secondary reaction.' As we have noted above, this situation is impossible in the classical scheme by Shilov, since the product of the primary reaction (I) P2 is not included in the final equation of the conjugate reaction."

However, according to Shilov ([9], p. 11) "... in view of the fact that an inductor enters a reaction that proceeds arbitrarily (the primary process) and undergoes chemical transformation, the free energy released by it can compensate for the formation of a substance that requires work input."

I.M. Emanuel and Knorre [11] stated in the textbook on chemical kinetics the following: "In order for the reaction to proceed with an increase in free energy, a source of power (free energy) is necessary. An inducing reaction can be such a source. The free energy released by an inducing reaction must be greater than the free energy absorbed by the induced reaction. The use of free energy released in chemical reactions for the implementation of other reactions associated with the first processes is crucial in biological systems".

The formulations given in [11], from a thermodynamic point of view, unambiguously indicate the fundamental role of "free energy released in the primary reaction to cover the free energy" of the endothermic reaction—so that the latter secondary reaction becomes spontaneous.

The main thesis of the authors against these formulations, including mine, is that "the product of the primary reaction is not included in the final equation of the conjugate reaction".

There is a complete misunderstanding in [8] of the fact that the highly active intermediate particle generated by the primary reaction, due to bifurcation, transforms the secondary thermodynamically obstructed reaction into a spontaneous one. At the same time, the stage mechanism of a complex secondary reaction always includes elementary reactions responsible for the formation of a common, highly active intermediate particle in the mechanism of the primary reaction. Thus, along with the common highly active particle, conjugate reactions have at least one common elementary reaction.

Interaction of reactions, as is known, occurs through a common highly reactive intermediate particle "or through the final product of a reaction, which is the catalyst of another reaction". In the first case, in the framework of the theory of conjugate reactions, a non-spontaneous induced reaction is caused and amplified by an inducing spontaneous reaction through a highly active common intermediate, which, being consumed in the secondary reaction, transforms it into the category of spontaneous ones.

The second case relates to autocatalytic reactions, where the catalysis effect can enhance only a spontaneous reaction, while conjugation of reactions allows a non-spontaneous reaction to be carried out, due to the consumption of a highly active general intermediate synthesized in it by the primary reaction.

Thus, on page 286 [8] there are confused arguments on the following "in the presence of common intermediates in sequential or parallel-sequential, (i.e. , kinetic conjugation), a correlation of rates occurs ...", which introduces formulations into chemical kinetics, that distort its basis.

Let us consider the mechanisms of sequential and parallel-sequential reactions, described in [8]:

$$A \rightarrow B \rightarrow C \qquad\qquad (19)$$

$$(20)$$

where C, and D are the final products that can be isolated, i.e. quite stable compounds. Substance B is an intermediate stable product of sequential and parallel- sequential reactions, and not a highly active common intermediate, due to which the conjugation of reactions is carried out in the system.

If we assume that substance B in the reaction (20) is a highly active common intermediate, then it ceases to be parallel-sequential in the accepted sense, and becomes the stage of the conjugate primary reaction. In this case B is the link between the two conjugate gross reactions, and its bifurcation leads to the formation of the final products C and D. Thus there is no need to mention sequential and parallel-sequential reactions, as is done in [8].

Only gross reactions that have a common, highly active intermediate which is a bifurcation center that cannot be isolated from the reaction medium can be conjugated. We have already noted above that in order to form a new modified mechanism of the secondary reaction, elementary stages are taken from the mechanism of the primary reaction, leading to the formation of a common highly active intermediate (bifurcation center) in the system. Because of the bifurcation mechanism, the initial form of the secondary reaction is transformed from a thermodynamically hindered reaction to a spontaneous one.
It is important to take into account the fact that common elementary stages of the primary and secondary reactions cannot functionally be a bifurcation center. The bifurcation center is their common intermediate, which is consumed in the subsequent stages of the conjugate reactions.

It is further stated in [8] that "... a decrease in free energy in the primary reaction fully covers the increase in free energy in the secondary reaction", this is impossible because the product of the primary (1)—P2 is not included in the final equation in the conjugate reaction (XVII). It is given in the textbook [15] and the monograph [13] that the joint occurrence of spontaneous ("conjugate", No. 2) and thermodynamically forbidden ("conjugate", No. 1) gross reactions, in the mechanism of which there is a common intermediate (or common intermediates), makes possible the flow of a thermodynamically forbidden process. Similar statements are given in [16,17]. "These unsubstantiated statements (on the possibility of a situation arising when A; R; <0) apparently appeared for the first time in the monographs" [18,19].

These considerations are summarized in [8] on page 287: "Thermodynamics of the primary exoergic reaction affects thermodynamic characteristics of the conjugate process only when a stoichiometric equation of the primary reaction fully enters a new final equation of the conjugate reaction along with an equation of the conjugate target reaction as a result of an occurrence of a chain of successive reactions".

In the first place, the primary reaction cannot fully enter the mechanism of the secondary reaction due to the fact that they are two independent gross reactions with their characteristic end products. Another thing is when the elementary stages of the primary reaction (see above) lead to the occasion when they participate in a transformation of a non-spontaneous secondary reaction into a spontaneous one with the help of the formed highly active intermediate substance (intermediate). Free energy of a chemical reaction is usually calculated from state of substances, in their initial and final states. Another way is when a stage mechanism of a complex reaction is known, wherein its free energy will be the sum of free energies of each elementary stage. This implies that the sum of the free energies of the elementary stages, which lead to the generation of a common highly active intermediate in the system, is added to the sum of the free energies of the subsequent stages, leading to the secondary reaction. Shilov, proceeding from the knowledge of his time (1905), justifiably believed that the free energy of the conjugating primary reaction should completely cover the free energy of the thermodynamically hindered secondary reaction. Based on today's knowledge, we see

that both approaches lead to identical conclusions and the authors of [15,13] quite rightly use Shilov's approach.

Thus, the final equation of the secondary reaction transformed into the spontaneous one should not include the final products of the primary reaction, as it is not correctly suggested in [8].

However, since the common intermediate is consumed in the secondary reaction, it is natural that the common initial substance of both conjugated reactions as an actor is included in the gross equation of this reaction.

Kinetic definitions in textbooks and monographs related to simple and complex parallel, parallel-sequential and conjugate reactions relate only to gross reactions, but not to the elementary stages of the mechanism of a separate gross reaction. These kind of obvious kinetic ideas are ignored in [8], and, therefore, the authors propose a new concept of "conjugation of elementary stages through common intermediates as a universal phenomenon" which has no scientific basis. Elementary stages that are part of the mechanism of the two conjugated reactions, as noted above, cannot influence and interact with each other due to the fundamental principle of chemical kinetics about the independence of their flow. As it has been mentioned above, they enter into the mechanism of the conjugate gross reaction because of the general highly active intermediate (bifurcation center). The interaction of the reactions can only be considered at the level of gross reactions, which are characterized by the use of terms parallel, sequential, parallel-sequential and conjugate reactions.

Moreover, it is stated in [8] that: "The final catalytic reaction of R ⇔ P does not proceed independently of the stages leading to it, which are

$$R + M \Leftrightarrow MR$$

(a)

And

$$MP \Leftrightarrow M + P$$

(b)
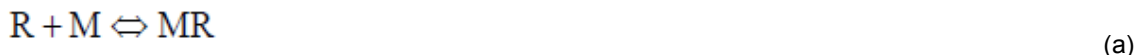
This two-stage mechanism involves kinetic conjugation of two stages through a common MR intermediate, however the final reaction does not conjugate anything".

The authors' claim that stages (a) and (b) have a common intermediate substance MR is very doubtful: for the stage (a) MR is the final substance, and for the reaction (b) it is the starting substance. So the question is: where is the general intermediate substance in this mechanism? It makes sense to speak of a common highly active substance in conjugated reactions only when it forms the basis of its bifurcation (it is the bifurcation center) [4,5].

It is given on p. 287 [8], ... a number of other statements in the manuscripts [15,13] seem very strange: ... that the TDS phenomenon can be considered for parallel stoichiometric reactions, i.e. stationary gross reactions, each of which is characterized by a certain chemical affinity (p. 332 of [13]).

Parmon V.N. correctly took the approach regarding conjugate processes, that only gross reactions can be conjugated [13]. It is surprising, that the authors of [8], on the one hand are categorical, and on the other hand, they reproach the authors [16,17] for not justifying their statements, while upholding their false perspectives about the conjugation of elementary stages.

It is stated on p. 287 of [8] that: "As for the 'synchronous' reactions, the 'chemical interference' and the 'coherence of chemical interference' [1,4,6], it should be noted that these concepts have no relation to the features of conjugate reactions or to the effect of thermodynamic conjugation. Pseudo-scientific terminology only obscures reasonably clear kinetic effects".

Synchronous reactions are nothing but simultaneous reactions and it is not quite clear why it is impossible to use this expression in this sense. The term "chemical interference" means that the primary reaction interferes with the flow of the secondary reaction and thereby conjugates with it. The authors' reaction [8] to this appropriate analogy is quite surprising. If I had used the expression "conjugate intervention of one reaction into the flow of another" instead of "conjugate interfering reactions" the authors [8] would not supposedly react negatively. It has already been noted that interfering (i.e. interfering into the flow of each other) reactions can be conjugate, initiated, catalytic reactions, etc.

The expression "coherence of chemical interference" means the consistency of chemical intervention of one reaction into the flow of another, and there is nothing unclear about it.

While claiming that "these concepts have no relation to the features of the conjugate reactions or to the effect of thermodynamic conjugation", the authors of [8] obviously did not understand obvious things and therefore we are not able to figure out their motive when they claim these quite clear terms as "pseudoscientific".

Based solely on their false notions that "Conjugation of the primary and secondary reactions according to Shilov is the kinetic conjugation of the elementary stages ..." the authors deny a validity of the existence of "thermodynamic conjugation" in "conventional understanding".

Summarizing all the above, we recall once again that simple reactions, due to their elementary nature, can never be conjugated, however much they are covered by "pseudoscientific terms" (as stated by the authors of [8]) such as "kinetic conjugation", "conjugation of elementary reactions", etc. Therefore, the statement on p. 282 [8] that "Kinetic conjugation of stages is a characteristic feature of all complex reactions" means only one thing: almost all complex chemical reactions known in nature are conjugate, and this contradicts the existence of a huge number of complex reactions outside of the system of conjugate reactions.

I consider it my duty to bring to the reader's attention that in 1994 and in 2000 I published two articles [2,3] purely devoted to conjugate reactions in the journal Physical Chemistry. In addition, in 1989 a monograph [1] was published in "Nauka" publishing house, the editor-in-chief of which was the famous physicist- chemist O.M. Poltorak. He wrote in his preface the following: "The theory of conjugate oxidation reactions also belongs to the parts of chemical kinetics, which, undoubtedly, need to be paid attention to at the present time. However, traditional branches of science almost never manage to be revived to life in their literal interpretation. They can acquire modern sound only with their creative modification, only with 'dialectical return' built on the use of new ideas and methods. It seems to me this is what exactly was done by famous Azerbaijani physicochemical doctor of chemical sciences T.M. Nagiev [18,19,20,21].

His concept of the interference of chemical reactions is a natural generalization and a non-trivial development of N.A. Shilov's idea of conjugate oxidation reactions". Only scientific practice will show whether the new concept of "interference of chemical processes" will be viable or not.

4. CONCLUSIONS

The strategy associated with imparting high efficiency and orderliness to chemical interference has proved itself:

1. The primary reaction runs with almost 100% conversion in the absence of the secondary reaction;
2. It approaches 100% selectivity for both reactions.

The study of chemical interference and its particular case of conjugated processes indicate that it may represent a simple prototype for similar systems realizable in biochemical systems.

First of all, realization of chemical interference is associated with the selection of those reactions that are capable of self-organization, i.e. to formation of complex reaction ensemble. The ensemble of molecules and, as a consequence, the ensemble of reactions is able to interfere, because the aggregation of molecules in ensembles somehow creates an algorithm for the realization of mutually agreed spontaneous reactions. Contrary to free molecules, the distinctive feature of an ensemble of molecules is the fact that structural organization of an ensemble of molecules allows running of both simple and complex reactions, chemical interference of which is vitally important for the living system activity. In this discussion we would like to indicate that chemical interference is the necessary property of biochemical systems. Note also that molecular ensembles may be differently organized structurally and, therefore, the type of ensemble from the same molecules is responsible for proceeding of one type of interrelated reactions or another (i.e. chemically interfering reactions).

The ensemble of reactions is self-organized through the intermediary of general highly active substances. These processes may be accelerated and effectively implemented with the help of catalysts similar to processes, which take part in the living systems.

Thus, self-organization of an ensemble of reactions capable of being intensified or weakened and, therefore, inducing chemical interference, may be suggested as the basis for the principle of organization of many enzymatic ensembles.

Of great interest is the creation of trigger reaction ensembles, which will not only change the interference picture but also the type of interacting reaction with respect to the action of temperature, pressure, medium pH and other important factors.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

1. Nagiev TM. Chemical Conjugation. Nauka. 1989;216.
2. Nagiev TM. Interrelated reactions and chemical interference. Russian Journal of Physical Chemistry. 1994;68:456-460.
3. Nagiev TM. Conjugated chemical reactions. Russian Journal of Physical Chemistry. 2000;74: 2034-2042.
4. Nagiev TM. Interaction of synchronous reactions in chemistry and biology. Baku, Sabail. 2001;404.
5. Nagiev TM. Coherent synchronized oxidation reactions by hydrogen peroxide. Elsevier, Amsterdam. 2007;325.
6. Nagiev TM. The theory of coherent synchronized reactions: Chemical interference logics. Materials Sciences and Application. 2015;6:152-170.
   Available:https://doi.org/10.4236/msa.2015.6201
7. Rius-Alonso C, González-Quezada Y, Pantoja FF, Ramírez JB. Visualizing the mechanisms of organic reactions. In Proceedings of ICERI Conference ISBN. 2013;978-84.
8. Bruk LG, Temkin ON. Conjugate reactions: New potentials of an old idea. Kinetics and Catalysis 2016;57:277-296.
   Available:https://doi.org/10.1134/S0023158416030022
9. Шилов НА. О сопряженных реакциях окисления. М: Типография Мамонтова. 1905;304.
10. Carey FA, Sundberg RJ. Study and description of organic reaction mechanisms. Advanced Organic Chemistry: Part A: Structure and Mechanisms. 2000;187-261.
11. Раковский АВ. Введение в физическую химию. 1938;683.
12. Sara G, Dan M, Gidon C. The fenton reagents. Free Radical Biology and Medicine. 1993;15: 435-445.
    Available:https://doi.org/10.1016/0891-5849(93)90043-T
13. Parmon VN. Thermodynamics of non-equilibrium processes for chemists with a particular application to catalysis. Elsevier, Amsterdam. 2010;321.
    Available:https://doi.org/10.1016/B978-0-444-53028-8.00001-0

14. Эмануель НМ, Кнорре ДГ. Курс химической кинетики. М: Высшаяшкола. С. 1969;233-289.
15. Бажин НМ, Иванченко ВА, Пармон ВН. Термодинамика для химиков. М: Химия, КолосС, с. 2004;416.
16. Prigogine I, Defay R. Chemical Thermodynamics. Longmans, Green. 1954;533.
17. Prigogine I, Condepudy D. Current Thermodynamics. From Heat Engines to Dissipative Structures. Mir, Moscow; 2002.
18. Nagiev TM. New approaches to simulation of enzymatic reactions: Mimetic catalysis. Journal of Chemistry: Education Research and Practice. 2019;3:1-2.
Available:https://doi.org/10.33140/JCERP.03.02.01
19. Nagiev TM. The theory of coherent-synchronized reactions: Chemical interference logics. International Journal of Chemical Engineering and Applications. 2015;6:293-305.
Available:https://doi.org/10.7763/IJCEA.2015.V6.500
20. Nasirova UV, Gasanova LM, Nagiev TM. Monooxidation of ethylene with hydrogen peroxide on the Per-FTPhPFe^{3+}OH/Al$_2$O$_3$. Russian Journal of Physical Chemistry A. 2010;84:941-945.
Available:https://doi.org/10.1134/S0036024410060099
21. Gasanova L, Mustafaeva C, Nagieva I, Abbasov A, Magerramov A, Terner J, Nagiev T. Selective biomimetic oxidation of ethanol by hydrogen peroxide on immobilized ironporphyrincatalysts. Russian Journal of Physical Chemistry A. 2005;79:382-388.

Biography of author(s)

Tofik Nagiev
National Academy of Sciences of Azerbaijan, Baku, Azerbaijan.

He is an author of macrokinetic theory of coherent-synchronous reactions interaction. He has both defined a concept of chemical interference and proposed an equation of determinant considering the condition of coherence as well as phase shifts for the reactions synchronized in time and space. This theory has been definitely proved by experiment. In the basic of enzymes of monooxygenase, peroxidase and catalase reactions was established new biomimetic catalyst and of this direction for the research result in biotechnology new biomimetic sensors has been elaborated. Research of recent years is concerned to biomimetic catalysis, development of high-performance hydroxylation and epoxidation catalytic biomimics resistant to the action of oxidant and high temperatures, the property of hydrogen peroxide to induce various reactions. In the row of fundamental scientific achievements the important place belongs to new   dependent elementary reactions with appropriate kinetic parameters proposed by him. Namely this circumstance has allowed him and his team to study new free-radical-induced reactions-oxidative fixation of atmospheric nitrogen, conjugated dehydrogenation of alkanes and alkenes, epoxidation, hydroxylation and oxidation of methane to methanol, formaldehyde hydrogen-containing gas. A certain contribution has been made to the study of chemical energy accumulation principles in the conjugated chemical and biochemical systems. In the meantime the scientific principles of creation of biomimetic sensors - new analytic systems are successfully elaborated under his guidance. Obtaining of nitrogen 1-oxide on the fixation mechanism of molecular nitrogen with hydrogen peroxide by the result of the quantum-chemical studies and existence of stable HOO–N=N–OOH intermediate was theoretically substantiated.

London Tarakeswar