An Application of Chemical Oscillation: Distinguishing Two Isomers between Cyclohexane-1,3-dione and 1,4-cyclohexanedione

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Abstract

In the analytical field, previous applications of chemical oscillation focused on quantitative analysis. We report in this paper a novel qualitative method electrochemically distinguishing two positional isomers by utilizing their perturbation effects on a catalyzed Briggs-Rauscher (BR) oscillation. The catalyst in the system is a macrocyclic nickel (II) complex $\text{NiL}(\text{ClO}_4)_2$, where the ligand L in the complex is 5,7,7,12,14,14-hexamethyl-1,4,8,11-tetraazacyclotetradeca-4,11-diene. The experimental results indicated that addition of cyclohexane-1,3-dione (1,3-CHD) or 1,4-cyclohexanedione (1,4-CHD) could affect the profiles of potentiometric oscillations, but their changes in the profiles are greatly different. When 1,3-CHD was injected into the oscillating system, there was an initial spiking of the oscillations, accompanying by quenching of oscillations before the regeneration of oscillations. While 1,4-CHD was injected into the dynamic mixture, the oscillatory system responded to the perturbation with only slight decrease followed by a sharp increase in the potential, before it resumed to its normal oscillation state. The perturbation of 1,3-CHD involves inhibition time, whereas the perturbation of 1,4-CHD does not. Hence these two positional isomers could be distinguished by using their different perturbation effects on a BR dynamic system in the range of 9.0×10^{-4} to 8.0×10^{-3} M. Our assumption is that, perturbation of 1,3-CHD on the oscillating system involves a radical oxidization process to produce carboxylic acid, whereas perturbation of

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1,4-CHD assumes iodination and elimination steps to form 1,4-benzoquinone. Such different perturbation mechanisms are responsible for the difference in potentiometric oscillation profiles change. This hypothesis was confirmed by products analysis by FTIR and UV spectra.

Keywords: Briggs–Rauscher; macrocyclic nickel complex; cyclohexane-1,3-dione; 1,4-cyclohexanedione

1.Introduction

Some chemical systems, being far from equilibrium, show nonlinear kinetic behaviors, such as periodic oscillations^[1], chaos^[2], wave propagation and pattern formation^[3]. Among such nonlinear systems, periodic chemical oscillation not only exhibits the unique kinetic behaviors but it has also been used as unique tools in the analytical field. For example, some quantitative approaches based on oscillatory reaction have been developed for determination of analytes by their perturbation effects on oscillating system since 1978 when the pioneer work was established by Tichonova et al.. Some succeeding developments in quantitative analysis include determination of irons (Ru^{3+} , Ru^{4+} , Hg^{2+}), gases (CO , NO , Cl_2)^[4] analysis, and organic reagent analysis^[5]. Strenuously, analysts utilized both the Belousov-Zhabotinsky (BZ) oscillating reaction and the Briggs-Rauscher (BR) oscillator, exploring the new domain where these two matrixes can be applied.

Like BZ oscillation which occurs in homogeneous solution, the BR system (an acidic solution of hydrogen peroxide, potassium iodate, malonic acid, and catalyst) exhibits typical periodic color changes from colorless to yellow to blue then to colorless with a starch indicator, making it an excellent demonstration in lab at its first emergence in history. Continuous studies on such reaction have revealed its complex mechanism, in which both the non-radical process and the radical process exist during oscillations^[6]. Understanding on its unique dynamics has helped analysts utilize BR as a matrix to measure some antioxidants activities^{[7]-[11]}. Antioxidant activities could be evaluated because antioxidants were found to function as free-radical scavengers to react with the radical intermediate in the BR system.

In our previous studies, we have shown that, some oscillating systems of BR

type or BZ type can act as suitable matrixes in measurement of abundant of analytes, such as eugenol^[12], Ag⁺^[13], pyrogallol^[14], catechol^[15], calcium pantothenate^[16] and alizarin red^[17]. Catalysts involved in these BR or BZ systems are macrocyclic complexes, [CuL](ClO₄)₂ or [NiL](ClO₄)₂ (Scheme 1), where the ligand L in the complex is 5,7,7,12,14,14-hexamethyl-1,4,8,11-tetraazacyclotetradeca-4,11-diene. The ligand of the complexes occupies the extended π -system, which ensures a high rate for reactions involving electron transfer at individual steps of the oscillating process^[18]. This character makes these chemical oscillatory matrixes vulnerable to the external perturbations. As previous applications of chemical oscillation focus on the quantitative analysis, we report in this paper a novel qualitative method for distinguishing two positional isomers of cyclohexane-1,3-dione (1,3-CHD) and 1,4-cyclohexanedione (1,4-CHD) (Scheme 2) by utilizing their perturbation effects on such a catalyzed BR oscillation.

Scheme 1. The structure of [NiL](ClO₄)₂, where the ligand L in the complex is 5,7,7,12,14,14-hexamethyl-1,4,8,11-tetraazacyclotetradeca-4,11-diene.

Some isomers are found tough getting separated and distinguished because they usually possess the same molecular weight, the same physical properties or even the same functional groups. In an attempt to distinguish the isomers, some instrumental methods like MS^[19], GC-MS^[20] and HPLC-NMR^[21] have been employed. The mass spectrometry (MS) is based on the distribution of ions by mass-to-charge ratio and hence it can measure the mass of a molecule. But the method has difficulty in distinguishing isomers because the ion fragments come from two isomers may have the same mass-to-charge ratio and similar distribution. By coupling the high separation efficiency of gas chromatograph (GC) with high sensitivity of mass

spectrum (MS), GC-MS method has the advantage of high sensitivity in distinguishing the isomers. But this technique does not work for some compounds with high boiling point because some molecules are prone to be decomposed at high operating temperature. Being insensitive to light and oxygen, the HPLC-NMR method possesses high separation and identification efficiency with high accuracy in structural analysis. However, one of its disadvantages is its low sensitivity. Another disadvantage is that it only works for small molecule but is not suitable for identification of macromolecular isomers. A new electrochemical method for distinguishing isomers is expected.

Scheme 2. (a) Structure of cyclohexane-1,3-dione (1,3-CHD); (b) Structure of 1,4-cyclohexanedione (1,4-CHD)

In this paper, an accomplishment for identification of two position isomers (1,3-CHD and 1,4-CHD) was achieved by using a Briggs–Rauscher oscillating reaction. The concentrations of 1,3-CHD and 1,4-CHD that can be distinguished is over the range from 9.0×10^{-4} to 8.0×10^{-3} M. Compared with our previous application of using BR reaction for quantitative measurement of analytes^[12-17], this electrochemical technology involving a BR reactor provides a new rapid qualitative method in identification of two isomers (1,3-CHD and 1,4-CHD) with simpler equipment.

2. Experimental.

2.1. Apparatus.

All chemicals used were of analytical reagent grade without further purification except for the catalyst $[\text{NiL}](\text{ClO}_4)_2$, which was synthesized according to a published procedure^[22,23] and identified by elemental analysis and IR spectrum. KIO_3 ,

malonic acid, H_2O_2 and sulfuric acid were obtained commercially from Sinopharm Chemical Reagent Co.,Ltd. Cyclohexane-1,3-dione (1,3-CHD) and 1,4-cyclohexanedione (1,4-CHD) were purchased from Shanghai Chemical Industry Development Co.,Ltd. 1,4-benzoquinone is the product of Shanghai Aladdin biochemical Polytron Technologies Inc. The solutions of 0.14 M KIO_3 , 2 M malonic acid, 4 M H_2O_2 , 0.0173 M $[\text{NiL}](\text{ClO}_4)_2$ and 0.5 M sulfuric acid were prepared in double-distilled water. The solutions of 1.5 M cyclohexane-1,3-dione, 1.5 M 1,4-cyclohexanedione and 0.1 M of 1,4-benzoquinone were made just before the experiment. All reaction solutions must be homogeneous.

2.2. Apparatus

The experimental assembly consists of an oscillation reactor (40 mL) and a potential measuring system. The reactor was coupled with a thermostat (model DZCS- II C, Nanjing Dazhankejiao Institute of Instrument, China) by which the system was kept at the temperature of 5°C in order to prolong the duration of the oscillations in the BR system, and a model 79-3 magnetic stirrer (Jiangsu, China) was used to homogenize the solutions. Digital potential measurements as a function of time were made by a personal computer (PC) which connected to an amplifier (Vernier Software Technology, USA), a Go!Link sensor interface (Vernier Software Technology, USA), and two electrodes. One of the electrodes is Pt electrode (Type 213, Shanghai Electricity and Light Instrumental Factory) which acts as working electrode, and the other is a saturated calomel electrode (SCE, Type 217, Shanghai Wei ye Instrumental Plant) via a salt bridge containing 0.5 M Na_2SO_4 which is used as reference electrode. The Logger Lite data-acquisition programme was used. IR measurements were taken by an infrared spectrometer (model Nexus-870 Nicolet 380, Shanghai HOMOO Urban Planning CO., Ltd) and Ultraviolet spectra measurements by a Ultraviolet spectrometer (model UV-1750, Shimadzu, Japan). A micro-pipette was also used in the experiments for injecting different amount of solution samples.

2.3 Procedure

In a 50 mL-reactor, oscillating reaction solution was made by mixing following solutions: 6 mL of 0.14 M KIO_3 , 3 mL of 2 M malonic acid, 2 mL of 0.0173 M

[NiL](ClO₄)₂, 2 mL of 0.5 M sulfuric acid, 13 mL double-distilled water and 14 mL of 4 M H₂O₂. This solution was vigorously stirred and the temperature was kept at 5 °C. To this solution, the potentials as a function of time were immediately recorded by immersing two electrodes into the solution and starting data acquisition program after the addition of H₂O₂. Once a regular oscillating profile appeared, different amounts of 1,3-CHD or 1,4-CHD solutions were injected at the sixth cycle in order to perform perturbation experiments. Each perturbation experiment was repeated at least three times to ensure the reproducibility.

3. Results and discussion

3.1. Action of distinguishing of two position isomers between 1,3-CHD and 1,4-CHD

In order to distinguish two position isomer, perturbation experiments were made by addition of the same amount of 1,3-CHD or 1,4-CHD into the BR system. We added 40 µL of 1.5 M of, 40 µL of 3.75 M of, or 20 µL of 3.75 M of 1,3-CHD solution into the BR system to make its concentration in the system reach 1.5×10^{-3} M, 3.75×10^{-3} M, or 7.5×10^{-3} M, respectively (Fig.1. b,d and f). Also, we added 40 µL of 1.5 M of, 40 µL of 3.75 M of, or 20 µL of 3.75 M of 1,4-CHD solution into the BR system to make its concentration in the system reach 1.5×10^{-3} M, 3.75×10^{-3} M, or 7.5×10^{-3} M, respectively (Fig.1. c,e and g). As it is shown in Fig.1, such a novel BR showed different responses to the perturbation of 1,3-CHD or 1,4-CHD. When 1,3-CHD was injected into the oscillating system, there was a sharp decrease followed by a quick increase in the potential (resulting in an initial spiking of the oscillation), accompanying by a period of time of quenching of oscillations (called inhibition time, namely, ΔT) before the regeneration of oscillations (Fig.1. b,d and f). While 1,4-CHD was injected into the dynamic mixture, the oscillatory system responded to the perturbation with only slight decrease followed by a sharp increase in the potential, after which it resumed to its normal oscillation state (Fig.1. c,e and g). If the BR oscillator was perturbed by 1,3-CHD, there would be an initial spiking of the oscillation followed by an inhibition time before restarting of oscillations. Perturbation of the oscillating system with 1,4-CHD only resulted in a slight decrease

followed by a sharp increase in the potential. The perturbation of 1,3-CHD involves inhibition time, whereas perturbation of 1,4-CHD does not. Thus, two isomers, 1,3-CHD and 1,4-CHD, could be distinguished by using their perturbation effects on a BR dynamic system. The concentrations range that these two isomers can be distinguished is from 9.0×10^{-4} to 8.0×10^{-3} M.

3.2. Mechanism of action of 1,3-CHD and 1,4-CHD on the oscillating system

3.2.1 Mechanism for the BR oscillating system

The difference in responses of such BR dynamics to these two isomers is related to their different perturbation mechanisms. Also, isomers perturbation mechanisms are based on the BR oscillation mechanism itself. In an attempt to interpret the difference in oscillation profiles caused by isomers perturbation, the BR oscillation mechanism itself is taking into consideration. Earlier reports on the classical BR oscillating chemical reactions showed that the radicals play an important role in the reactions. Based on original NF^[24] and DE^[25], the mechanism for the oscillating reaction was proposed in reactions (1) – (12):

The reactions (1)-(5) involve the iodine:

The generation of oxygen is shown in the reactions (6)-(7):

The reaction (8)-(9) involves the oxidation and reduction of catalyst:

The formation of oxygen is also involved in the reaction (10)

The organic substrate/iodine reactions are shown in reactions (11)-(12):

3.2.2. The reaction between the 1,3-CHD and the intermediate $\text{IO}_2\bullet$ in the oscillator

Usually, the radical $\text{IO}_2\bullet$ is known to have a strong oxidation ability in an acid medium while 1,3-CHD is regarded as a good reduce agent because it contains the ketone groups which could be oxidized into carboxylic acids. When 1,3-CHD was added to the oscillating mixture, it would react with the intermediate $\text{IO}_2\bullet$ to form the corresponding dicarboxylic acid. The reaction equation was expressed as follow

In order to explore the oxidation product of 1,3-CHD in an oscillation mixture, we added 1,3-CHD into the system of $\text{KIO}_3\text{-H}_2\text{SO}_4\text{-H}_2\text{O}_2\text{-NiL}$. We did not include malonic acid in such a system for two reasons. One is that oxidation product of 1,3-CHD is produced by an oxidation process while malonic acid can not play as such a role as an oxidation reagent. The other reason is that, if malonic acid is present, there would be difficulty in separating organic oxidation product of 1,3-CHD from malonic acid which is also an organic compound. In such a condition, there would be the interference between IR spectrum of malonic acid and the IR spectrum of organic oxidation product, by which the organic oxidation product was identified. Absence of malonic acid will solve this problem. We noticed that the inhibition time is about 150 seconds, and such period of time is the time elapsed for oxidation of 1,3-CHD in the oscillation system, so the experiment for oxidation of 1,3-CHD in the system of $\text{KIO}_3\text{-H}_2\text{SO}_4\text{-H}_2\text{O}_2\text{-NiL}$ should be terminated in 150 seconds to avoid being overoxidation. Hence, after an interval of 150 seconds counting from the addition of 1,3-CHD into the system of $\text{KIO}_3\text{-H}_2\text{SO}_4\text{-H}_2\text{O}_2\text{-NiL}$, termination of oxidation of 1,3-CHD was conducted by quickly adding 1 M NaOH solution to mixture to neutralize acid, because IO_3^- or H_2O_2 can act as strong oxidation reagents only in an acid medium. The pH value of the mixture was monitored by a pH electrode while NaOH solution was added. We stopped adding NaOH when pH value of the solution

reached 7.8. The solid was obtained from the mixture through rotary evaporation of the solution. The organic product (products) in this solid is the organic oxidation product from 1,3-CHD, though there may exist, in the solid, little amount of inorganic product(s) KI. It is known that KI shows no interference on the IR spectra of the organic oxidation product. The IR spectrum of the solid was shown in the Fig.2., which also represents the IR spectrum of organic oxidation product from 1,3-CHD.

As it is shown in Fig 2., an absorption band at 1589 cm^{-1} ^[26] is assigned to the dissymmetry stretching vibration (fig.3(a)) of the carbonyl bond ($\text{C}=\text{O}$) in carboxylate anion, while another absorption at 1390 cm^{-1} is assigned to the symmetrical stretching vibration mode (fig.3(b)) of carbonyl bond ($\text{C}=\text{O}$) in carboxylate anion. This confirms that carboxylate anion exists in the solid and it comes from oxidation of 1,3-CHD. While being added into the system of $\text{KIO}_3\text{-H}_2\text{SO}_4\text{-H}_2\text{O}_2\text{-NiL}$, 1,3-CHD was oxidized into carboxylic acid which was converted into carboxylate anion by adding the NaOH solution.

The response of the oscillating system to the addition of 1,3-CHD is understood as followings: because 1,3-CHD is a reducing reagent, electric potential of reaction mixture decreased when 1,3-CHD was injected into the normal BR system. Then 1,3-CHD reacts with $\text{IO}_2^\bullet$ radical to form dicarboxylic acid. Such reaction can consume $\text{IO}_2^\bullet$ radical, and the decrease in the concentration of $\text{IO}_2^\bullet$ radical will make the reaction (5) shift to the right, resulting in the decrease in the concentration of HIO_2 according to reaction (5). The decrease in the concentration of HIO_2 will result in the increase in the $[\text{NiL}]^{3+}$ concentration according to reaction (8). Based on the Nernst equation ($E=E^\circ+0.0592/n \lg[\text{NiL}]^{3+}/[\text{NiL}]^{2+}$), the potential will increase. As there was an initial decrease followed by an increase in potential, an initial spiking of the oscillations was observed. Precisely because of the reaction by which the intermediate radical $\text{IO}_2^\bullet$ was consumed, an inhibition time was observed. When the 1,3-CHD was consumed completely, the oscillations could restart.

3.2.3. The action of 1,4-CHD on the oscillating system

The final product of 1,4-CHD with BR oscillating system needs to be verified.

Keresztúri and Szalai^[27] have shown that, in a BR oscillating system, 1,4-CHD is oxidized into 1,4-benzoquinone. The reaction is shown as follow:

In order to confirm the reaction between 1,4-CHD and BR oscillating system with the formation of 1,4-benzoquinone, UV spectrum measurements were made by using a Ultraviolet spectrometer (model UV-1750, Shimadzu, Japan).

In a beaker, solutions were added in following order: 1 mL of 1 M H_2SO_4 , 6 mL of 0.14 M KIO_3 , 1 mL of 1 M 1,4-CHD and 32 mL double-distilled water. The mixture solution was kept for 24 h until all 1,4-CHD was converted into the product. Then the mixture solution was taken for UV spectrum measurements. Also, measurements of the UV spectrum 1,4-benzoquinone solution were taken. The results of the experiment were shown in Fig.4.

The obtained graphs of absorbance vs. wavelength show that the pure 1,4-benzoquinone and the mixture 1,4-CHD- H_2SO_4 - KIO_3 have the same maximum absorption at the wavelength of 250 nm. The result indicates that 1,4-CHD could be oxidized into 1,4-benzoquinone by injection of it into this BR system.

We performed the perturbation experiments by using 1,4-benzoquinone instead of 1,4-CHD. The perturbation experiments have shown that, just like the 1,4-CHD which have effects on the B-R system (Fig.1), 1,4-benzoquinone exhibits the similar perturbation effects on the B-R system. When 1,4-benzoquinone was injected into the B-R system, the oscillatory system responded to the perturbation with slight decrease followed by a sharp increase in the potential, after which it resumed to its oscillation state with increased amplitude (Fig. 5). Because the concentration of 1,4-benzoquinone is a much higher than that being converted from 1,4-CHD, increases in amplitude were observed. Lower concentration of 1,4-benzoquinone

should result in no increases in amplitude. Such 1,4-benzoquinone perturbation experiments confirm that 1,4-CHD was oxidized into 1,4-benzoquinone.

4. Conclusions

We demonstrated that, for the first time, a macrocyclic Ni(II) complex-catalyzed BR oscillator could be utilized as a suitable tool in electrochemically distinguishing two positional isomers of 1,3-CHD and 1,4-CHD. The different perturbation mechanisms of these two isomers on the BR system result in the difference in potentiometric oscillation profiles change, which could be employed in qualitative analysis. We revealed that, 1,3-CHD is oxidized into carboxylic acid by radical $\text{IO}_2\bullet$, whereas 1,4-CHD is converted into 1,4-benzoquinone.

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Figure 1. Oscillation profiles for the proposed BR system in the condition: (a) unperturbed oscillation; (b) perturbation of 1.5×10^{-3} M of 1,3-CHD in the system; (c) perturbation of 1.5×10^{-3} M of 1,4-CHD in the system; (d) perturbation of 3.75×10^{-3} M of 1,3-CHD in the system; (e) perturbation of 3.75×10^{-3} M of 1,4-CHD in the system; (f) perturbation of 7.5×10^{-3} M of 1,3-CHD in the system; (g) perturbation of 7.5×10^{-3} M of 1,4-CHD in the system; Common conditions: $[\text{H}_2\text{SO}_4]=0.025$ M; $[\text{KIO}_3]=0.021$ M, $[\text{H}_2\text{O}_2]=1.4$ M, $[\text{Malonic acid}]=0.015$ M, $[\text{NiL}]=8.65 \times 10^{-4}$ M, $T = 5^\circ\text{C}$

Figure 2. IR spectrum of the solid

Figure 3. (a) Dissymmetry stretching vibration of the carbonyl; (b) Symmetrical stretching vibration mode of carbonyl

Figure 4. (a) The UV spectrum of pure 1,4-benzoquinone; (b) The UV spectrum of 1,4-CHD- H_2SO_4 - KIO_3

Figure 5. Responses of the BR system to perturbation of 1,4-benzoquinone. The conditions: $[\text{KIO}_3]=0.021$ M; $[\text{MA}]=0.15$ M; $[\text{H}_2\text{SO}_4]=0.025$ M; $[\text{NiL}]=0.865$ mM; $[\text{H}_2\text{O}_2]=1.4$ M; $[1,4\text{-benzoquinone}]=3.75 \times 10^{-5}$ M

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Graphical Abstract