Micelles in Physical Chemistry Laboratory. Surfactant Catalyzed Oxidation of Glycine by Acidic Permanganate

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INTRODUCTION

This study of micellar catalyzed and uncatalysed oxidative decarboxylation of glycine by potassium permanganate in moderately concentrated acid medium is an ideal and simple kinetic experiment for secondary level and undergraduate chemistry laboratory. This shows how the presence of surfactant affects the reaction rate, dependence of the reaction rate on the concentrations of substrate and oxidant. Efforts are also made to impart training to write the most pertinent reaction mechanism for the reaction under consideration. Using excess concentrations of glycine, the depletion of permanganate is monitored iodometrically. Various graphs to ascertain the first order kinetics have been drawn. The reaction follows pseudo-first-order kinetics. The overall reaction is second order, with first-order dependence on both permanganate and glycine. Then the effect of variation of surfactant concentration on the reaction rate was studied. Positive cooperativity index value is obtained graphically to establish the pre-micellar catalysis. The experiment is feasible in 3-4 hours of lab session. Thus this has been found to be a good experimental chemical activity to be undertaken.

Theory of Surfactant catalysis

Surfactants have attracted considerable interest in theoretical and experimental fields due to their catalytic effects and behaviour as analogous to biological membranes. They have a tendency to associate i.e. at a certain concentration in solution their monomers associate to form larger aggregates. The surfactant molecules always contain both polar (hydrophilic) and non-polar (hydrophobic) moieties they thus tend to concentrate at interfaces. Surfactants can be separated into two main types, ionic and non-ionic, the former dissociate in water. Ampholytic surfactants contain both types of functional groups but only one of them is active at a given pH of the medium. The ionic surfactant monomer is completed by an ion of the opposite charge, called a counter-ion (in cationic surfactant it is usually a halide; in anionic surfactant it can be an alkali-metal cation). The hydrophobic group is generally a hydrocarbon chain (R) of 10 to 20 carbon atoms. The hydrophilic portion may ionise or it may not. At the lower concentration surfactant molecules consist in the monomeric state in aqueous solution. However as the concentration increases they begin to self-associate and form a new pseudophase as they reach the critical micelle concentration (cmc).

Critical micelle concentration

Surfactants dissolve completely in water at very low concentration, but above a certain concentration, they have a tendency to associate i.e. at a certain concentration in solution, their monomers associate to form larger micelle aggregates. This concentration is characteristic for each surfactant and is termed critical micelle concentration (cmc). In fact, as the concentration of surfactant in the solvent increases the diphilicity of the molecules which begins to cause association to form larger particles.

What is micellar catalysis?

One of the important properties of micellar system is their ability to affect the rates of the chemical reaction. The effect of surfactants on reaction kinetics is called micellar catalysis. The physical basis for micellar catalysis involves several contributing factors. Micellar catalysis of reactions in aqueous solutions is usually explained on the basis of a distribution of reactants between water and the micellar “pseudophase”. The reaction occurs at different rates in the two media. If the solubility of the reactants is greater in the micelles than in water then the local concentration is increased in the micelle, often with suitable orientation of the reactants bound in the micelle. This leads to a large increase in the effective concentration and the observed rate (in terms of moles per unit time per liter of the entire solution) increases accordingly leading to an increase in the reaction rate. The relative free energies of the reactions and/or the transition state can be altered when reaction takes place in the micellar phase instead of bulk water. This concept is reminiscent of catalysis by an enzyme and many initial studies of rates in micellar system focussed on this possibility. Further, it was thought that only electrostatic interaction occurs between micelles and reactants,
however, later it was revealed that reaction rates are also affected by hydrophobic interactions. Catalytic effect increases with increasing hydrophobicity of the micelles and reactants. A simple surfactant catalysis can be ascertain by plotting a graph between \( k \) versus \([D]\) but to describe the dependence of rate constant on \([D]\) in pre-micellar region we propose a Piszkiewicz model. If a graph between log \([k_{\text{obs}}-k_0]/(k_m-k_{\text{obs}})\] versus log \([D]\) is linear and the slope value falls between 1-6 this confirms the pre-micellar catalysis. Here, \(k_0\) is rate constants in the absence of surfactant, \(k_{\text{obs}}\) is the observed rate constant at any concentration of surfactant and \(k_m\) is the maximum rate constant obtained in the presence of surfactant.

**EXPERIMENTAL**

**Preparations of chemicals**

Following chemicals were used. Potassium permanganate (BDH), sulphuric acid (AR), glycine (Merck), soluble starch (AR), sodium thiosulphate (AR), SDS (Aldrich), potassium iodide, oxalic acid, sodium hydroxide and deionised water.

**Apparatus**

Burette (50 mL), pipette (10 mL), conical flask (125 mL), burette stand, porcelain white plate.

**Preparation of Solutions**

Students are being advised to refer to the book “A textbook of quantitative inorganic analysis” by A. I. Vogel. This gives data regarding the strength of various acids, corresponding to their percentage or normality and specific gravities and also how much volume of each acid should be taken and diluted to 1000 mL in order to prepare 1 M solution.

**Potassium permanganate (M/50)**

By dissolving 0.790 g of potassium permanganate in water (deionised) so as to make the final volume of solution 250 mL, thus we get M/50 permanganate solution.

**Sulfuric acid**

The stock solution of sulphuric acid can be prepared by dilution of known volume of acid d. 667mL of (18 M) \( \text{H}_2\text{SO}_4 \) is made up to 1000 mL will give 12 M \( \text{H}_2\text{SO}_4 \). The solution is so prepared can be standardized against the solution, NaOH previously standardized against standard solution of oxalic acid. While making the sulfuric acid of desired strength, care is to be taken that concentrated \( \text{H}_2\text{SO}_4 \) should be added in installment of few mL to the water and not water to the acid. In case water is added to the acid, intense heat evolves which may break the container.

**Oxalic acid (3M)**

The standard solution of oxalic acid (\( \text{H}_2\text{C}_2\text{O}_4 \cdot 5\text{H}_2\text{O} \)) was prepared by direct weighing 37.8 g of oxalic acid into water to make the final volume 100 mL.

**Sodium hydroxide**

We want to prepare stock solution of 3M sodium hydroxide in 100 mL water. For this 12 g of NaOH has to be dissolved in water. It is advised to weigh about 18 g of NaOH to dissolve in water to make the final 100 mL. We have waited slightly more NaOH because quantitative dilution of this solution give us standard solution of 3 M. Before dilution the solution was standardized by titrating it against the standard oxalic acid solution.

**Glycine (1.5 M)**

The molecular weight of glycine is 75, therefore, 112.5 g of glycine dissolved in water to get the final volume of one liter so as to get 1.5 M solution.

**Sodium thiosulphate (Hypo) (M/200)**

M/200 solution of Sodium thiosulphate (\( \text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O} \)) can be prepared by dissolving 1.860 g of it in 1500 mL of water. In order to avoid standardization care is to be taken that stock solution should remain the same throughout the experiment.

**Potassium iodide (1%)**

This is done by weighing 1 g of KI and dissolving into 100 mL of water.

**Starch solution (1%)**

Soluble starch was taken approximately 1 g on a watch glass, and a paste of it was prepared by adding a few drops of water to it. About 100 mL of water was taken in separate beaker and warmed up to 70-90 °C and then the previously prepared paste was added drop by drop with constant stirring to this warm water. A faintly opalescent solution of
1% starch is thus prepared.

**Sodium dodecyl sulphate (M/100)**

The stock solution of the detergent (M/100) was prepared by dissolving 0.288 g of SDS in 100 mL of water. Care is to be taken that the solution should not be shaken vigorously otherwise lots of bubbles will be formed which will take great time to settle down, consequently the work will be delayed.

**PROCEDURE, RESULTS AND DISCUSSION**

The reaction has been studied iodometrically. Take 35 mL of glycine solution (1.5 M), 10 mL of water and add 5 mL of sulfuric acid (12 M). Shake it well. Now add 5 mL of potassium permanganate solution, in the reaction mixture bottle. Note down the time. Shake the reagent bottle for about two minutes. Need not to worry about the zero reading. After stirring and shaking thoroughly, pipette out 10 mL of the reaction mixture. Add 5 mL of 1% potassium iodide in the conical flask. Iodine will be liberated, reaction will stop between \( \text{MnO}_4^- \) and glycine. \( \text{I}_2 + \text{I}^- \rightarrow \text{I}_3^- \) complex will be formed, hence no loss of iodine due to evaporation. Titrate flask solution against hypo till the pale yellow colour appears now add a few drops of starch solution. The solution becomes blue. The hypo is to be added till blue color disappears. Note the burette reading. As the reaction proceeds and \( \text{MnO}_4^- \) is consumed, lesser \( \text{MnO}_4^- \) will liberate lesser \( \text{I}_2 \) and consequently less hypo is required. Readings are to be taken after every ten minutes of interval and tabulated. About 75% of the reaction is to be studied. A perusal of the table reveals that the value of rate constant \( k \) was found to be constant. This confirms that the reaction between glycine and permanganate is first order kinetics. Further, this could be confirmed by drawing various graphs. For the first order kinetics the graphs between \( \log (a-x) \) vs. \( t \) and \( \log a/a-x \) vs. \( t \) must be straight line, and specifically the straight line in the case of \( \log a/a-x \) vs. \( t \) plot should pass through the origin. Volume of hypo added is used instead of concentrations for \( a \) and \( a-x \) as the advantage of first order kinetics. All the desired plots are in complete agreement with the expected pattern. In a typical kinetic run (Table 1) for the reaction \([\text{Glycine}]=0.525 \text{ mol dm}^{-3}, [\text{MnO}_4^-]=1.0\times10^{-3} \text{ mol dm}^{-3}, [\text{H}_2\text{SO}_4]=6 \text{ mol dm}^{-3}, \text{Temp}=28 \degree \text{C}\). The rate constant \( k \) has been found to be \( 1.40\times10^{-2} \text{ min}^{-1} \) i.e. the slope value multiplied by \(-2.303\). The order with respect to \([\text{glycine}]\) in order to get the order of reaction with respect to glycine concentration kinetic runs were carried out with varied concentrations of glycine (Table 2) and keeping the concentrations of other reagents

---

**Table 1. Typical run**

<table>
<thead>
<tr>
<th>time/min</th>
<th>( a )</th>
<th>( (a-x) )</th>
<th>( \log (a-x) )</th>
<th>( \log (a/a-x) )</th>
<th>( k ) /10^{-2} \text{ min}^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6.7</td>
<td>-</td>
<td>0.8260</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>5.9</td>
<td>0.7708</td>
<td>0.055</td>
<td>1.26</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>5.3</td>
<td>0.7242</td>
<td>0.101</td>
<td>1.16</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>4.6</td>
<td>0.6627</td>
<td>0.163</td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>4.1</td>
<td>0.6127</td>
<td>0.213</td>
<td>1.22</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>3.4</td>
<td>0.5314</td>
<td>0.294</td>
<td>1.35</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>2.7</td>
<td>0.4623</td>
<td>0.363</td>
<td>1.39</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>2.3</td>
<td>0.3979</td>
<td>0.428</td>
<td>1.39</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>2.0</td>
<td>0.3424</td>
<td>0.483</td>
<td>1.38</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>1.8</td>
<td>0.3010</td>
<td>0.525</td>
<td>1.33</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 1. Typical run.** \([\text{Glycine}]=0.525 \text{ mol dm}^{-3}, [\text{MnO}_4^-]=1.0\times10^{-3} \text{ mol dm}^{-3}, [\text{H}_2\text{SO}_4]=6 \text{ mol dm}^{-3}, \text{Temp}=28 \degree \text{C}\).
constant. The plots of log k vs. log [glycine] gave straight lines with slopes 0.99 [Fig. 3], suggesting the reaction has first-order dependence with respect to [glycine].

**Effect of addition of surfactant**

This reaction has been found to be catalyzed by addition of sodium dodecyl sulfate, [Table 3]. The reaction rate increases with the increase in the detergent concentration from $2.0 \times 10^{-4}$ to $20 \times 10^{-4}$ M. The reported cmc of sodium dodecyl sulfate is $8.1 \times 10^{-3}$ M at 25 °C. Reports are available that the catalysis below cmc i.e. premicellar catalysis is also feasible. As discussed earlier in the theoretical treatment for pre-micellar catalysis a graph is plotted between log $[k_{obs} - k_0] / [k_m - k_{obs}]$ and log [D]. The plot is a good straight line with slope value n=2.37. This figure is drawn using the table-3. In this graph $k_0$ is the first value of the from the table i.e. without surfactant, $k_m$ is the value of rate constant with surfactant concentration from $2.0 \times 10^{-4}$ to $20 \times 10^{-4}$ mol dm$^3$ and $k_{obs}$ is the maximum rate constant in the presence of surfactant concentration $20 \times 10^{-4}$ mol dm$^3$.In this way for every next value of surfactant we get a new $k_{obs}$ value. Just put these values in

![Graph](image1)

**Table 3. Change in rate constant on variation of [SDS]**

<table>
<thead>
<tr>
<th>[SDS]/10$^{-4}$ mol dm$^{-3}$</th>
<th>$k_{obs}/10^{-2}$min$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nil</td>
<td>0.47</td>
</tr>
<tr>
<td>2.0</td>
<td>2.02</td>
</tr>
<tr>
<td>3.0</td>
<td>3.63</td>
</tr>
<tr>
<td>4.0</td>
<td>5.65</td>
</tr>
<tr>
<td>6.0</td>
<td>12.40</td>
</tr>
<tr>
<td>8.0</td>
<td>20.70</td>
</tr>
<tr>
<td>10.0</td>
<td>24.49</td>
</tr>
<tr>
<td>20.0</td>
<td>38.60</td>
</tr>
</tbody>
</table>

$k_{m} = 38.60 \times 10^{-2}$ min$^{-1}$

![Graph](image2)

**Fig. 3. Variation of substrate concentration.** [MnO$_4^-$]=1.0 × 10$^{-3}$ mol dm$^{-3}$, [H$_2$SO$_4$]=6 mol dm$^{-3}$, Temp=28 °C.

![Graph](image3)

**Fig. 4. Positive Cooperativity, Change in rate constant on variation of [SDS].** [Glycine]=0.225 mol dm$^{-3}$, [MnO$_4^-$]=1.0 × 10$^{-3}$ mol dm$^{-3}$, [H$_2$SO$_4$]=6 mol dm$^{-3}$, Temp=28 °C.
log \[k_{\text{obs}} - k_0 / k_m - k_{\text{obs}}\] and draw a graph against log [D]. The n value obtained is between the expected value for pre-micellar catalysis i.e. between 1 to 6. This value on n supports the substrate promoted micellization. This lower value of n suggest the pre-micellar catalysis because in the case of micellar catalysis this value has to be more than 20.

**Mechanism**

According to Frost and Pearson\(^9\), a reaction mechanism is a mental model. Regarding the mechanism, it is advised for the students to read E. L. King’s\(^10\) book “How chemical reactions occur”. According to this book, if the order of reaction with respect to substrate is one, then it should appear once on the left-hand side in the various steps in the form of equilibrium. Therefore, glycine should appear once on the left-hand side. The order with respect to KMnO\(_4\) is also one, it should also appear once in the reaction scheme, whether it appears earlier or later it makes no difference. Glycine, which is an amino acetic acid, is an internal salt and present in the form of zwitter ion.\(^11\) The carboxyl group has the ability to lose a proton (acidity) where as the amino group may accept a proton (basicity). Hence the molecule is polar and has a high dipole moment.

\[
H_2O \quad H_2N - CH_2 - COOH \rightleftharpoons H_3N^+ - CN_2 - COO^- (1)
\]

In order to avoid the precipitation of MnO\(_2\) the reaction in being carried out in moderately concentrated acid medium, high concentration of proton will protonate the zwitter ion. Since NH\(_2\) part is already having a positive charge, therefore, the most likely place to which proton could get attach is carboxyl oxygen. Thus, the next step is as follow:

\[
H_2N + CH_2COO^- + H^+ \rightleftharpoons NH_3CH_2COOH (2)
\]

The order with respect to permanganate is also one, it should also appear on the left hand side once. Hence,

\[
\text{MnO}_4^- + H^+ \rightleftharpoons \text{HMnO}_4^- (3)
\]

This step is consistent with the spectroscopic evidence of existence of molecular HMnO\(_4\), therefore, cumulative effect explains the catalysis by mineral acid as well\(^1\) but not given here as beyond the scope of the students at secondary level. HMnO\(_4\), a more powerful species of MnO\(_4^-\) now reacts with protonated zwitter ionic species of glycine, in the presence of water molecule.

\[
\text{HN}_{\text{CH}_3\text{COOH}} + \text{HMnO}_4 + \text{H}_2\text{O} \quad \overset{k_1}{\longrightarrow} \quad \text{HN}_{\text{CH}_3\text{COOH}} + \text{HMQ} + \text{H}_2\text{O} + \text{H}^+ (4)
\]

This three-body collision is difficult and thus explains the cause of slowness in the slowest reaction. Most suitable conformation and configuration of the activated complex is necessary for this reaction to take place. Since this occur statistically per second, in a very small number, the eqs 4 becomes very slow. All subsequent steps are very fast and not of kinetic importance. Moreover, all kinetic and activation data are explainable with the help of step 2 to the rate determining step, i.e step 4. Our purpose is to deduce mechanism from kinetic data. This could be shown in the following paragraphs and from the deduction rate law expression. The probable reactions (fast) after the rate determine are as follows:

\[
\text{HN}_{\text{CH}_3\text{COOH}} \quad \overset{\text{Fast}}{\longrightarrow} \quad \text{HN}_{\text{CH}_3\text{COOH}}^- (5)
\]

\[
\text{HN}_{\text{CH}_3\text{COOH}}^- + \text{HMQ} \quad \overset{\text{Fast}}{\longrightarrow} \quad \text{HN}_{\text{CH}_3\text{COOH}}^- + \text{HMnO}_4^- + \text{H}_2\text{O} + \text{H}^+ (6)
\]

\[
\text{HN}_{\text{CH}_3\text{COOH}}^- + \text{H}_2\text{O} \quad \overset{\text{Fast}}{\longrightarrow} \quad \text{HCHO} + \text{NH}_3 + \text{H}^+ + \text{H}_2\text{O} (7)
\]

In order to derive rate law apply the law of mass action to the equations 2 - 4, from eqn.2 we get,

\[
K_i = \frac{[\text{HN}_{\text{CH}_3\text{COOH}}]}{[\text{H}_2\text{O}][\text{H}^+]}
\]

From eqn.3

\[
K_i = \frac{[\text{HMnO}_4^-][\text{H}^+]}{[\text{MnO}_4^-][\text{H}^+]}
\]

But we know that free [MnO\(_4^-\)] = initial [MnO\(_4^-\)] - [HMnO\(_4\)] formed

\[
\text{HN}_{\text{CH}_3\text{COOH}}^- + \text{H}_2\text{O} \quad \overset{\text{Fast}}{\longrightarrow} \quad \text{HCHO} + \text{NH}_3 + \text{H}^+ + \text{H}_2\text{O}
\]
Or $[\text{HMnO}_4] = K_1 [\text{MnO}_4^-] [\text{H}^+]$
Or $[\text{HMnO}_4][1+K_1[\text{H}^+]] = K_1 [\text{MnO}_4^-] [\text{H}^+]
Or [\text{HMnO}_4] = K_1 [\text{MnO}_4^-] [\text{H}^+]/[1+K_1[\text{H}^+]] \quad (9)$

Now from eqn.4

$$-d[MnO_4^-]/dt = k_1 [\text{NH}_3\text{CH}_2\text{COOH}][\text{HMnO}_4][\text{H}_2\text{O}] \quad (10)$$

Substituting the values of $[\text{NH}_3\text{CH}_2\text{COOH}]$ and $[\text{HMnO}_4]$ from 8 and 9 in eqn 10 we get

$$-d[MnO_4^-]/dt = \frac{k_1 K_2 [\text{H}^+]^2 [\text{H}_2\text{O}]}{(1+K_1[\text{H}^+]})$$

At a given concentration of acid

$$-d[MnO_4^-]/dt = k [\text{Glycine}][\text{MnO}_4^-]\quad (11)$$

where $k = \frac{k_1 K_2 [\text{H}^+]^2 [\text{H}_2\text{O}]}{(1+K_1[\text{H}^+]})$

**Surfactant catalyzed mechanism:**

In the presence of an anionic surfactant SDS the reaction rate has been found to be substantially increased. This is most probably due to the electrostatic interaction between substrate and anionic surfactant globules. This leads to increase in effective concentration and may provide favourable orientation for the collision, thus the reaction rate increases. The first step is the formation of glycine-surfactant complex. The lower value of $n$ substantiates this because the number of detergent molecules otherwise expected in a micelle is around 20. The substrate surfactant interaction is the main cause of premicellar catalysis. In this light the proposed mechanism is thus as follows:

$$n\text{SDS} + \text{NH}_3\text{CH}_2\text{COOH} \rightleftharpoons \text{SDS} \quad \text{slowest}$$

$$\text{NH}_3\text{CH}_2\text{COOH} \quad \text{substrate-surfactant complex}$$

$$\text{NH}_3\text{CH}_2\text{COOH} \ldots (\text{SDS})_n + \text{HMnO}_4 + \text{H}_2\text{O} \rightarrow$$

$$\text{NH}_3\text{CH}_2\text{COO}^- + \text{HMnO}_4 + \text{H}_2\text{O} \quad \text{(13)}$$

In order to derive rate law apply the law of mass action to the equations 12 -13, from

eqn.12 we get,

$$K_c = [\text{SDS}]_{\ldots \ldots} \text{NH}_3\text{CH}_2\text{COOH}/[n \text{SDS}][\text{NH}_3\text{CH}_2\text{COOH}]$$

Or $[\text{SDS}]_{\ldots \ldots} \text{NH}_3\text{CH}_2\text{COOH} = K_c [n \text{SDS}][\text{NH}_3\text{CH}_2\text{COOH}] \quad (14)$

From eq.13

$$-d[MnO_4^-]/dt = k [\text{SDS}]_{\ldots \ldots} \text{NH}_3\text{CH}_2\text{COOH}$$

$$[\text{HMnO}_4][\text{H}_2\text{O}] \quad (15)$$

Since the catalyzed and uncatalysed reactions take place simultaneously, substitute the values of $[\text{HMnO}_4]$ and $[\text{SDS}]_{\ldots \ldots} \text{NH}_3\text{CH}_2\text{COOH}$ from 9 and 14 in eqn 15, and combining it with the uncatalysed reaction i.e. equation 4, we get the rate law as:

$$-d[MnO_4^-]/dt = \frac{k_2 k_3 K_2 [\text{H}^+]^2 [\text{H}_2\text{O}]}{(1+K_1[\text{H}^+]})$$

$$[\text{SDS}]^n \text{[NH}_3\text{CH}_2\text{COOH}][\text{MnO}_4^-] \quad (16)$$

At a given concentration of acid

$$-d[MnO_4^-]/dt = k^* [\text{SDS}]^n [\text{Glycine}][\text{MnO}_4^-]$$

where $k^* = \frac{k_2 k_3 K_2 [\text{H}^+]^2 [\text{H}_2\text{O}]}{(1+K_1[\text{H}^+]})$

or $-d[MnO_4^-]/dt = k_{obs} [\text{SDS}]^n [\text{MnO}_4^-] \quad (16)$

Where $k_{obs} = k^* [\text{Glycine}]$

It is evident from the rate law equation 16 that substrate and surfactant complex is the cause of catalysis. Surfactant catalysis is purely a physical catalysis and there is no covalent type of bond formation takes place.

**Conclusion:** The proposed experimental chemical education exercise well tested and easy to perform at secondary and undergraduate level laboratory to impart an understanding of order of reaction, determination of rate constants, the surfactant catalysis, effect of variation of reactant concentrations on the rate of the reaction and how to write a most probable reaction mechanism.
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