Diels-Alder Reaction in microemulsions with ionic liquid

Huihong Lü, Xueqin An, Jianguo Yu and Xingfu Song

The Diels-Alder Reaction (DAR) between N-ethylmaleimide and 2,3-dimethyl-1,3-butadiene was studied in microemulsions with ionic liquid (IL) for the first time. The apparent second-order rate constants were determined by spectrophotometry in the microemulsion. The effect of solvent on the DAR rate was investigated and interpreted. The experimental results showed that the reaction rate in the microemulsion with IL was enhanced and it was faster than that in pure isooctane and in generic AOT microemulsion. The effect of the IL on the apparent second rate constant ($k_2$) was explained. The effect of temperature on the reaction rate was studied, and values of apparent activation energy were estimated in various microemulsion with IL.

**Keywords:** apparent activation energy; apparent rate constant; Diels-Alder Reaction; kinetics; microemulsions with ionic liquid; solvent effect

INTRODUCTION

The Diels-Alder reaction (DAR) is an intensively used cycloaddition that enables the synthesis of complex polycyclic molecules with fine control over the stereochemistry. At present, much attention is devoted to the syntheses of biologically active reaction products and the ways of designing desired molecules by the DAR. The mechanism of DAR has been subject of heated debate. Although DAR can proceed without the need for catalysts, the reactions are sometimes slow and need to be accelerated by physical methods such as high pressure, high temperature, ultrasound irradiation. The acceleration of the reactions through solvent is more attractive as it avoids high temperature, high pressure and additives.

The acceleration of the reactions through ultrasound irradiation.

**Materials and Methods**

**Materials**

Sodium bis[2-ethylhexyl]sulfosuccinate (AOT, 99%) was vacuum-dried in a desiccator for 1 day prior to use without further purification.

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DIELS-ALDER REACTION KINETICS IN MICROEMULSION

Cetyltrimethylammonium bromide, isooctane and n-pentanol were AR-grade reagent. N-Ethylmaleimide was with no less than 98% purity. The IL 1-butyl-3-methylimidazolium tetrafluoroborate (IL) was with no less than 99% purity.

Methods

Apparatus

The spectral equipment is 8453E diode array UV-vis spectrophotometer with a thermostated (stability of ± 0.05 K) multiple cell holder. The wavelength range is 190 to 1100 nm. The resolutions of the wavelength and absorbance are 1 nm and 1 x 10^-6 A, respectively.

Preparation of solutions

EM (0.0628 g) was dissolved with isooctane in a 100 ml volumetric flask, and the EM isooctane solution (5.00 x 10^-3 M) was obtained.

In a typical run, AOT and water were dissolved in the above EM isooctane solution, and a homogeneous AOT-EM microemulsion was prepared. According to experimental desire, a series of water/AOT/isoctane Ms with various AOT concentrations (C_AOT) and molar ratio (ω) of water to AOT were prepared.

Appropriate IL aqueous solution was added into the AOT-EM microemulsion, and a homogeneous EM IL-microemulsion was prepared. According to experimental desire, a series of EM IL-Ms with various C_AOT and ω were prepared, where IL and EM concentration are 2.7 x 10^-2 M and 2.50 x 10^-2 M in the EM IL-microemulsion, respectively.

Kinetic measurements

On the basis of kinetic measurements by spectrophotometry, it is important to ensure the stability of reactants. In order to check the stability, the reactants and product of the reaction were stored separately in Ms and IL-Ms for 24 h and did not find any competitive reaction. Therefore, it indicates that the kinetics measurements by this method are reliable.

A series of IL-microemulsion with various EM concentrations (C_EM) was prepared, and the absorbances of IL-Ms with various EM concentrations were obtained in the IL-Ms at fixed absorbed wavelength (296 nm) and temperature (298.15 K). The absorbance values of IL-Ms with fixed C_AOT (0.100 M) and ω (10) are shown in Table 1. The relationship between EM concentration and absorbance was shown in Fig. 1. The molar absorption coefficient (κ) of EM was obtained, and it was 807.4 L·mol⁻¹·cm⁻¹. The relating EM concentration (C_EM) and absorbance (A_EM) show good linear relationship within the certain conditions. Given the excess of DB, these reactions followed pseudo-first-order kinetics. The kinetics of the reaction was studied spectrophotometrically by running the reaction in the thermostat cells of spectrophotometer at different temperature. The absorbance variation with time was recorded at fixed absorbed wavelength of 296 nm. The kinetics of reaction was studied under pseudo-first-order conditions and initial rate method.

RESULTS AND DISCUSSION

Kinetics of the DAR in the IL-microemulsion

The DAR between EM and DB can be considered as a second-order reaction. Therefore, the reaction rate can be expressed as:

\[ r = -\frac{dC_{EM}}{dt} = k_2 \times C_{EM} \times C_{ED} \]  

(1)

\[ C_{EM} \] and \[ k_2 \] are the concentrations of EM and DB, and the second-order reaction rate, respectively. When \[ C_{DB} \] is much excess to \[ C_{EM} \] (as in this study, \[ C_{DB}/C_{EM} = 100:1 \]), the change of \[ C_{EM} \] in the system can be neglected and considered as a constant. We make \[ k_1 = k_2 C_{DB} \] and then:

\[ r = -\frac{dC_{EM}}{dt} = k_2 \times C_{EM} \times C_{DB} = k_1 \times C_{EM} \]  

(2)

The reaction can be regarded as a pseudo-one-order reaction; \[ k_1 \] is the pseudo-one-order reaction rate constant.

Table 1. The absorption (\( \lambda_{max} = 296 \) nm) of various \( C_{EM} \) in the IL-Ms at 298.15 K

<table>
<thead>
<tr>
<th>( C_{EM} \times 10^{-3} ) M</th>
<th>A(EM,296 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>0.1858</td>
</tr>
<tr>
<td>0.50</td>
<td>0.3085</td>
</tr>
<tr>
<td>1.00</td>
<td>0.7983</td>
</tr>
<tr>
<td>2.00</td>
<td>1.6262</td>
</tr>
<tr>
<td>2.50</td>
<td>1.9890</td>
</tr>
<tr>
<td>3.00</td>
<td>2.3523</td>
</tr>
</tbody>
</table>

Figure 1. The absorbances of various \( C_{EM} \) in the IL-Ms at fixed absorbed wavelength (296 nm) and temperature (298.15 K)
According to the Lambert–Beer Law:

$$A = e l C_{EM}$$  \hspace{1cm} (3)

where $A$, $e$, and $l$ are the value of absorbance (at $\lambda_{max} = 296$ nm), molar absorption coefficient of EM and optical path of the quartz cell, respectively, and $l$ and $e$ are constants. Therefore, we can obtain the following equation:

$$\frac{dA}{dt} = -k_1 \times A = -k_2 \times C_{DB} \times A$$  \hspace{1cm} (4)

We make Eqn (4) to be definite integral, and Eqn (5) can be obtained:

$$\ln A_t = \ln A_0 - k_1 t$$  \hspace{1cm} (5)

where $A_0$ and $A_t$ are the values of absorbance (at $\lambda_{max} = 296$ nm) at $t = 0$ and $t = t$, respectively.

Creating graphs of $(-\ln A_t \sim t)$, the slopes of the corresponding plots is the pseudo-one-order reaction rate $k_1$. Then, we can obtain $k_2$ by Eqn (6):

$$k_2 = k_1 / C_{DB}$$  \hspace{1cm} (6)

EM maximum absorbance wavelength ($\lambda_{max} = 296$ nm) was selected to trace the reaction. The absorbency ($A$) of EM was measured at various reaction times by UV–vis spectrophotometer. For the DAR, Fig. 2 illustrates the good linear relationship between $-\ln A$ and time ($s$) in the IL-microemulsion with fixed $C_{AOT}$ (0.500 M) and $\omega$ (25) at 313.15 K ($R^2 = 0.9999$). Therefore, it is reasonable to obtain $k_2$ by the above descriptive method.

The effect of molar ratio of water to surfactant ($\omega$) and surfactant concentration ($C_{AOT}$) on the apparent second-order rate $k_2$ in the IL-Ms

The IL-water pool of IL-microemulsion can be considered as a microreactor that provides special medium and enhances or retards reaction rates. In this work, IL-Ms were considered as an alternative reaction media for DA reactions (Fig. 3), where solubility problems can be overcome. The reaction rate was effected by the IL-water pool nature and the concentration of surfactants in the IL-Ms. In order to explore the effect of microstructure and nature of IL-water pool on the apparent reaction rate constant, a series of the DA reactions was studied in the IL-Ms with various $C_{AOT}$ concentrations ($C_{AOT}$) and molar ratios of water to surfactant ($\omega$), and results were listed in Table 2. The apparent second-order rate constants ($k_2$) in the IL-Ms with

![Figure 2](image-url)

**Figure 2.** The relation between $-\ln A$ and time(s) for the DA reaction in IL-microemulsion with fixed $C_{AOT}$ (0.500 M) and $\omega$ (25) at 313.15 K

![Figure 3](image-url)

**Figure 3.** Sketch map for water pool of the IL-microemulsion system

<table>
<thead>
<tr>
<th>$T/K$</th>
<th>$C_{AOT}/M$</th>
<th>$k_2/(10^4k_2/M^{-1}s^{-1})$ for various $\omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\omega = 2$</td>
</tr>
<tr>
<td>298.15</td>
<td>0.100</td>
<td>1.01</td>
</tr>
<tr>
<td>0.200</td>
<td></td>
<td>1.14</td>
</tr>
<tr>
<td>0.300</td>
<td></td>
<td>1.37</td>
</tr>
<tr>
<td>0.400</td>
<td></td>
<td>1.54</td>
</tr>
<tr>
<td>0.500</td>
<td></td>
<td>1.72</td>
</tr>
<tr>
<td>0.600</td>
<td></td>
<td>1.80</td>
</tr>
<tr>
<td>303.15</td>
<td>0.100</td>
<td>1.29</td>
</tr>
<tr>
<td>0.200</td>
<td></td>
<td>1.69</td>
</tr>
<tr>
<td>0.300</td>
<td></td>
<td>1.95</td>
</tr>
<tr>
<td>0.400</td>
<td></td>
<td>2.06</td>
</tr>
<tr>
<td>0.500</td>
<td></td>
<td>2.40</td>
</tr>
<tr>
<td>0.600</td>
<td></td>
<td>2.68</td>
</tr>
<tr>
<td>308.15</td>
<td>0.100</td>
<td>1.73</td>
</tr>
<tr>
<td>0.200</td>
<td></td>
<td>2.13</td>
</tr>
<tr>
<td>0.300</td>
<td></td>
<td>2.69</td>
</tr>
<tr>
<td>0.400</td>
<td></td>
<td>2.89</td>
</tr>
<tr>
<td>0.500</td>
<td></td>
<td>2.94</td>
</tr>
<tr>
<td>0.600</td>
<td></td>
<td>3.04</td>
</tr>
<tr>
<td>313.15</td>
<td>0.100</td>
<td>2.40</td>
</tr>
<tr>
<td>0.200</td>
<td></td>
<td>2.88</td>
</tr>
<tr>
<td>0.300</td>
<td></td>
<td>3.55</td>
</tr>
<tr>
<td>0.400</td>
<td></td>
<td>3.62</td>
</tr>
<tr>
<td>0.500</td>
<td></td>
<td>4.14</td>
</tr>
<tr>
<td>0.600</td>
<td></td>
<td>5.53</td>
</tr>
</tbody>
</table>
various $\omega$ and $C_{AOT}$ at 313.15 were shown in Fig. 4. The apparent rate constant $k_2$ increases with $\omega$; this is because the IL-water pool size increases with $\omega$, which also results in increase of water content and polarity for the IL-Ms. The IL-water pool average radius ($R_m$) can be obtained by the relation of $R_m$ and $\omega$ ($R_m(\text{nm}) = 0.15\omega + 0.44$, given by Pilén[52]). Therefore, the DAR rate enhancement probably ascribed to increase solvent polarity[23,16,20,53] and enhanced hydrogen bonding.[11,19,20] On the other hand, the slight increase of rates with $\omega$ also indicates that the reaction mainly takes place at the IL-water pool interface rather than in the IL-water pool, because there should be a remarkable enhancement of $k_2$ if the DAR performances are in IL-water pool. The results shown in Fig. 4 indicate that the apparent rate constant increases with AOT concentration ($C_{AOT}$) in the IL-Ms. It may be due to the number of IL-water pool in the IL-Ms increases with AOT concentration,[50] and it brings on change of microenvironment polarity, interface and IL-water pool microstructure. Consequently, increase of both $\omega$ and $C_{AOT}$ results in the reaction rate increase. Otherwise, due to a low concentration of IL in the microemulsion, it was reasonable to consider IL as a regulator of the structure of IL-water pool rather than catalyzer.[44,47–49] A possible structure of resulting IL-water pool surrounded by fixed AOT film with a IL-palisade layer is schematically given in Fig. 3. The microemulsion formation and the change of diffusion coefficients can be influenced by the

Table 3. The apparent second-order rate constant ($k_2$) of the DAR in microemulsions (H$_2$O/AOT/Isooctane) at 313.15 K

<table>
<thead>
<tr>
<th>$C_{AOT}/M$</th>
<th>$10^4k_2/M^{-1}s^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega=2$</td>
<td>2.45 2.49 2.52</td>
</tr>
<tr>
<td>$\omega=5$</td>
<td>2.90 3.05 3.30</td>
</tr>
<tr>
<td>$\omega=10$</td>
<td>3.24 3.52 3.90</td>
</tr>
<tr>
<td>$\omega=15$</td>
<td>3.56 4.12 4.40 4.81 5.37 5.62</td>
</tr>
<tr>
<td>$\omega=20$</td>
<td>3.60 4.29 5.05 5.39 5.86 6.30</td>
</tr>
<tr>
<td>$\omega=25$</td>
<td>4.18 4.54 5.36 6.21 7.17 7.80</td>
</tr>
</tbody>
</table>

The effect of solvent on the reaction rate

In order to probe the effect of solvent on the DA reaction rate, the DAR was investigated in pure isoctane, IL and various Ms. Apparent reaction rate constant ($k_2$) was obtained in pure isoctane at 313.15 K, and it was $1.745 \times 10^{-4}$ M$^{-1}$s$^{-1}$, which is

![Figure 4](image1.png)  
**Figure 4.** The apparent second-order rate $k_2$ in the IL-microemulsion with various $\omega$ and $C_{AOT}$ at 313.15 K

![Figure 5](image2.png)  
**Figure 5.** Comparison of apparent reaction rate in different solvents at 313.15°C

![Figure 6](image3.png)  
**Figure 6.** The apparent second-order rate $k_2$ in the Ms with various $\omega$ and $C_{AOT}$ at 313.15 K

![Figure 7](image4.png)  
**Figure 7.** The DAR rates depending on the mole ratio of water to AOT in Ms and IL-Ms at a temperature of 313.15K

IL, but no notable changes in the structure or radius of nanoemulsion droplets were observed by SANS.[47–49]
similar to those obtained in other organic solvents except water. 1-Butyl-3-methylimidazolium tetrafluoroborate (IL) is an alternative reaction media for the DA reaction; the \( k_2 \) was \( 3.016 \times 10^{-3} \text{ M}^{-1} \text{s}^{-1} \) at 313.15 K, which is at least 10 times higher than that in the isooctane (Fig. 5). Based on the studies made so far, the advantages and enhanced rate of using ILs have been discussed in several reports. The IL shows polarity reflecting the influence of the polarity on the reaction rate as only one of the effective solvent parameters in the DAR. This also means that the IL may be inert compared to water when it acts as a solvent.

The DAR were studied in water/AOT/isoctane Ms with various C\(_{\text{AOT}}\) and \( \omega \) ([water]/[AOT]), and the apparent reaction rate constants (\( k_2 \)) were listed in the Table 3 and shown in Fig. 6. The \( k_2 \) of the DAR in the Ms shares the similar trend on the aspect of the effect of C\(_{\text{AOT}}\) and \( \omega \) on reaction rates in the IL-Ms (Fig. 4), because of increase of both water content (enlarge \( \omega \)) and number of water pool (enlarge C\(_{\text{AOT}}\)). In addition, the \( k_2 \) increases with increasing surfactant concentration due to the reactants being captured by the AOT molecule; therefore, the DAR takes place in the interface where there is a number of water. Combining with taking the limited water solubility of DB and EM into account, it is the result of the reaction largely taking place at the interface, where it was much faster than that in an organic solvent. The reason is the excellent solubilization, particular orientation and local concentration gradient effects at the interfaces (or concentrating reagents in the stern layer); therefore, the rates were enhanced.

On the side, an important influence on the rate constants caused by the changes in the structural properties of IL-water pool in the Ms has been observed as was confirmed by the water 1H NMR signals. Figure 7 shows a comparison of apparent reaction rate in Ms and IL-Ms, and the \( k_2 \) in IL-Ms is larger than that in Ms. Due to a low IL concentration in the Ms, it was reasonable to consider IL as a regulator of the polarity and microstructure of IL-water pool rather than catalyst. Recently, there were great structural changes in the isotropic phase when IL was entered into sodium dodecyl sulfate microemulsion. Low amount of IL can effect remarkably curvature adjustment in Ms. Combining the effect of the different effects of C\(_{\text{AOT}}\) and

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**Figure 8.** Apparent reaction rate constant (\( k_2 \)) increases with temperature in the IL-Ms systems with fixed C\(_{\text{AOT}}\) (0.6M) and \( \omega \) (20)

**Figure 9.** The plots of \( -\ln k_2 - C_{\text{AOT}} \) in the IL-Ms systems with various \( \omega \) (●\( \omega \) = 2; ○\( \omega \) = 5; ▼\( \omega \) = 10; ◀\( \omega \) = 15; ■\( \omega \) = 20; □\( \omega \) = 25) at different temperatures: (a) 298.15 K; (b) 303.15 K; (c) 308.15 K; (d) 313.15 K
The effect of temperatures on the apparent rate constant $k_2$ and activation energy $E_a$

The temperature has a strong influence on the apparent reaction rate as shown in Table 2. Figure 8 illustrates the $k_2$ increases with temperature in the IL-Ms with fixed $C_{AOT}$ (0.6M) and $C_2$ (20); it is because the microstructure and water properties of IL-water pool in IL-Ms were altered by temperature.\(^{[50,51]}\) Figure 9 reveals plots of $\ln k_2$ versus $C_{AOT}$ in the IL-Ms with various $\omega$ at different temperature. The relationship between $ln k_2$ and $C_{AOT}$ was near linear at various reaction temperatures.

The most important information of solvent effect on the reaction rate can be given by activation energy $E_a$, which shows the reaction barrier between reactants and products. The Arrhenius Law usually applies to elementary reactions in a simple solvent.\(^{[12]}\) However, it is also useful to estimate $E_a$ by that way in order to check up the influence of IL-Ms compositions in the complex system.\(^{[53]}\) For the DAR in the IL-Ms, the apparent activation energy $E_a$ was estimated by using Arrhenius Law, and the relationship between apparent activation energy $E_a$ and $\omega$ was shown in Fig. 10 for the DAR in the IL-Ms systems with fixed $C_{AOT}$ (0.500 M) and $C_2$ (0.027 M). As it can be seen, there is a decreasing trend of $E_a$ with $\omega$ increase. This may be due to the water property of IL-water pool in the IL-Ms is more like the bulk water by increasing $\omega$ (enhance water content), which results in the strong hydrogen bonding at the interface of IL-water pool and the reactants.

### CONCLUSIONS

Kinetics of DAR between N-EM and 2,3-DB were studied systematically in IL-microemulsion (IL-H$_2$O/AOT/isooctane). The apparent reaction rate constants were obtained, and they increase with both $\omega$ and $C_{AOT}$ in the IL-microemulsion systems. The effect of various solvents on the DAR rate was investigated, and results were shown that the rate constant $k_2$ in both microemulsion and IL-microemulsion are roughly four to five times higher than that in the isooctane, and the $k_2$ in pure IL are at least 10 times higher than that in the isooctane. The results indicate that high temperature accelerates the reaction and the apparent activation energy $E_a$ decreases with the increase of $\omega$.

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