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## Determination on temperature gradient of different polar reactants in reaction mixture under microwave irradiation with molecular probe

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#### ABSTRACT

Temperature accurate measurement is one of key issues in illustration of the rate increase in the microwave-promoted organic reactions because reaction rates are closely related with reaction temperature. The use of molecular probe is reported as a tool to identify the microwave selective heating effects in homogenous reaction mixture of intramolecular aromatic Claisen rearrangement. Our results show direct evidence for localized superheating of polar reactants in nonpolar solvent. While in the polar solvent, the microwave selective heating effects of polar reactants will be decreased.

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### 1. Introduction

Since the first published report in 1986,<sup>1</sup> microwave-assisted organic synthesis has been widely developed. Virtually all types of thermally driven chemical reactions have been studied under microwave irradiation.<sup>2</sup> Under microwave irradiation conditions, some organic reactions can be accelerated obviously. In some cases, this powerful technique can produce higher yields, different selectivity, and lower side products.<sup>3</sup> Such useful performances of microwave irradiation (MWI) have sparked considerable speculations and discussions into the essence of the microwave heating. Much of the debate has focused on the question whether the acceleration can be rationalized by purely thermal effects or some specific microwave effects.<sup>4</sup>

Nonthermal microwave effects<sup>4a,c</sup> were speculated previously as results from the directly coupling interaction between microwave electric field and polar molecules (reactants, intermediates, and even transition states) in the reaction mixtures, which did not generate a macroscopic change in reaction temperature. It was argued that microwave electric field affected the orientation of polar molecules or intermediates and hence changed the preexponential factors A or the activation energies in the Arrhenius equation for certain types of reactions.<sup>4a,d</sup> However, some of the further studies on the hypothesized nonthermal effects were proven incorrect later. Subsequent careful reinvestigations revealed that the reaction results were quite close to those of the conventional reactions run at the same temperature. The so-called 'microwave effects' were mainly due to the flawed temperature measurement of the reaction mixture or subtle differences of reaction conditions.<sup>4e,5</sup>

The vast majority of microwave accelerated reactions can be explained as the thermal effects arising from the extremely fast heating rate, which cannot be reproduced by classical heating. By using an external heat source, heat first passes through the walls of the vessel and then reaches the reaction mixture. It results in the temperature of reaction mixture being lower than that of the vessel until sufficient time to achieve thermal equilibrium. Microwave irradiation, on the other hand, directly couples with the molecules inside the reaction mixture, leading to a rapid rise in temperature.<sup>6</sup> Microwave irradiation does not change the activation energy, but provides the momentum to overcome the energy barrier of reactions more quickly. In addition, the 'inverted heat transfer' effect<sup>7</sup> (from the reaction mixture towards the exterior) can arouse the overheating of liquids above the normal boiling point,<sup>8</sup> since boiling nuclei are formed at the surface of the liquid. This overheating effect could explain the acceleration of reactions.





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While some specific reaction results under microwave irradiation could not be rationalized simply by rapid heating or flawed temperature measurement. For example, Yamada and co-workers reported a copper triflate-catalyzed asymmetric Claisen rearrangement,<sup>9</sup> in which the reaction was accelerated under the microwave irradiation without a corresponding decrease in enantioselectivity. The linear relationship between  $\ln[ee]$  and 1/Twas revealed that the enantioselectivity decreased as the internal reaction temperature increased.

MW energy directly heats specific molecules in the reaction mixture through the loss processes. For a specific molecule, the ability to convert microwave energy into heat is determined by the loss tangent (tan  $\delta$ ).<sup>6</sup> Compounds with high loss tangent tend to absorb the MW energy whereas less polar substances are poor absorbers. In this way, absorption of the radiation and heating may perform selectively.

Huang and Richert proposed a microwave selective heating model that the flow of microwave irradiation can potentially trigger the selective heating of a dipolar molecule in a non-absorbing solvent.<sup>10</sup> The microwave absorbing molecules ('domains') assimilate microwave energy and accumulate the heat, resulting in an instantaneous localized superheating ('hot spots'). The amount of accumulated heat can potentially give rise to microwave specific rate enhancement.

Schmink and Leadbeater used in situ Raman spectroscopy as a tool for probing the selective heating effects of microwave irradiation.<sup>11</sup> Raman monitoring can detect reaction mixture on a microscopic level. While the microwave energy may interact with the polar molecules more so than with nonpolar ones, the results indicate that more polar molecules are not at a higher temperature. They conclude that the reason is that the conversion of electromagnetic energy into kinetic energy is slower than conversion of kinetic energy into thermal energy. That is, the selective heating of microwave irradiation could not cause the microscopic 'hot spots'.

The experimental evidence of MW selective heating that is in accord with the model of Huang and Richert was reported by Dudley's group.<sup>12</sup> They observed detectable heat accumulation and microwave specific rate enhancement for the aromatic Claisen rearrangement of allyl 4-nitrophenyl ether in benzene (a nonpolar solvent). The effective temperatures calculated from the measured reaction rate based on Arrhenius plots were higher than the temperature measured by the calibrated internal fiber probe, demonstrating the excess heat is accumulated in the 'domain' and resulting in a reaction accelerating. This unique MW selective heating mechanism cannot be duplicated by convective heating process.

Generally, in order to evaluate or to attest the existence of MW effects, the temperature of the reaction mixture must be accurately measured. Unfortunately, currently common temperature monitoring devices, such as external infrared monitors and internal fiber monitors, are not the best choices to measure the internal temperature of reactions veritably and accurately.<sup>4e,13</sup> External infrared temperature monitors record the temperature on the outer surface of the reaction vessel and do not precisely reflect the temperature of the reaction mixture. Internal fiber-optic monitors are more accurate but only measure the temperature at several single positions of the reaction mixture. Importantly, in selective heating mechanism, the 'domains' can directly couple with microwave energy and thus create microscopic hot spots at the molecular level. The temperature gradient between 'domains' and surroundings, if exists, cannot be measured by commercially available temperature monitoring devices.

Molecular probes have advantage in the measurement of internal temperature of reaction mixture on molecular level compared with the physical temperature monitoring devices. Our group used diastereoselectivity in the Staudinger reaction as a useful probe for investigation of nonthermal microwave effects.<sup>14,15</sup> The results indicate that no obvious effect of microwave irradiation on the diastereoselectivity was observed in the Staudinger reactions. The increase of polarity of intermediates did not accelerate the reaction or alter the diastereoselectivity.

In this study, our group uses reactant molecules as a temperature probe in an effort to identify the microwave selective heating effects in homogenous reaction mixture. In this way, temperature gradient can be directly observed.

#### 2. Results and discussion

For a specific material or solvent, the ability to convert microwave energy into heat at a given frequency and temperature is determined by the so-called loss tangent (tan  $\delta$ ). The value of loss tangent is expressed as tan  $\delta = \epsilon'' | \epsilon'$ , where  $\epsilon''$  is the dielectric loss, indicative of the efficiency with which the electromagnetic radiation is converted to heat, and  $\varepsilon'$  is the dielectric constant describing the polarizability of molecules in the electric field. In general, materials with large permanent dipole moment could strongly absorb microwave energy and, consequently, for efficient heating.<sup>5,7</sup> In this study, we prospect to use a two-substrate-based aromatic Claisen rearrangement of allyl 4-nitrophenyl ether (ANE) and allyl 4methylphenyl ether (AME) as a tool for probing the selective heating effect of microwave irradiation on molecular level (Scheme 1). Aromatic Claisen rearrangements are suitable as model reactions because they are typical intramolecular reaction followed simple first-order kinetics. The effective temperature is easy to be obtained from the measured rate constants and Arrhenius Equation. With a significantly large dipole moment, ANE could effectively convert MW energy into heat, and the accumulated heat will, in our hypothesis, potentially create a high thermal energy 'domain', whereas the weak-polar AME could slightly absorb the MW energy and only be heated by the surroundings through the convective heating in polar solvent. Therefore, AME is considered likely to be suitable as a temperature probe for the bulk solution. This protocol does not require calibrated temperature monitoring devices and the strict control of microwave reactor. It can simulate the reaction conditions applied widely in microwave-assisted organic reactions.



**Scheme 1.** Two-substrate-based aromatic Claisen rearrangement of allyl 4-nitrophenyl ether (ANE) and allyl 4-methylphenyl ether (AME).

Solvents play a very important role in microwave-assisted organic reactions. The more polar a solvent is, the greater its ability to couple with the microwave energy and the faster the temperature of the reaction mixture increases. Clearly, the solvent effect is of great importance with regard to the possibility of the microwave selective heating. We conducted the same Claisen rearrangements under microwave irradiation both in a polar solvent (*N*-methylpyrrolidone, NMP, a favorable microwave absorbance solvent with loss factor tan  $\delta$  0.275) and in a nonpolar one (*n*-tetradecane). All of the reaction mixtures described in this report were macroscopically homogeneous and effectively stirred. The heating curves at 50 W of microwave power are shown in Fig. 1. The heating rate and the steady-state temperature of 0.1 M of ANE and AME in *n*-tetradecane are markedly different. n-Tetradecane shows little microwave heating in its pure form, but when 0.1 M of ANE is dissolved in it. the stronger heating is observed (the steady-state temperature is 158 °C). The weak polar AME is heated poorly under microwave irradiation and the heat rate and steady-state temperature of a 0.1 M solution of AME dispersed in *n*-tetradecane are almost the same as the pure *n*-tetradecane. These heating performances are extremely suitable for our investigation that the strong microwave absorbing ANE plays the role of 'Molecular radiator' and reacts at a higher effective temperature. While in the polar solvent NMP, the heating curves are almost the same. As a result, the selective heating would be shaded to a certain extent and the effective temperature of ANE and AME will, as our prospects, be the same.



**Fig. 1.** (a) Microwave heating curves of 0.1 M allyl 4-methylphenyl ether and allyl 4nitrophenyl ether in *n*-tetradecane at 50 W of applied microwave power; (b) Microwave heating curves of 0.1 M allyl 4-methylphenyl ether and allyl 4-nitrophenyl ether in NMP at 50 W of applied microwave power.

Before embarking on an investigation of microwave assisted reactions, the kinetic behaviors of the reactions were studied in a preheated temperature-controlled oil bath. The reaction temperature was carefully controlled within less than  $\pm 1$  °C with a fine temperature controller in a big oil bath with a large amount of silicone oil, and a thick asbestos coating outside the bath. The disappearance of ANE and AME was measured as a function of time at six different temperatures between 180 °C and 215 °C in *n*-tetradecane and five different temperatures between 170 °C and 210 °C in NMP. The plots of the natural logarithms of the concentrations of ANE and AME versus time at each temperature followed the expected first-order kinetics. The concentrations of ANE and ANP present in solution were determined by means of HPLC with

naphthalene as an internal standard. The measured rate constants are summarized in Tables 1 and 2 (For details, see Supplementary data, sections 3 and 4). The parameters of the Arrhenius equation are obtained from the measured rate constants (Figs. 2 and 3).

With the Arrhenius parameters in hand, we subsequently tested the MWI reactions under constant temperature conditions because the use of constant temperature mode is common in microwaveassisted organic reactions, particularly when adapting procedures developed under conventional heating conditions. In this study, all reactions were conducted under open vessel and constant temperature conditions. All microwave-assisted reactions were conducted in a commercially available microwave reactor, CEM Discover system<sup>™</sup>, equipped with an infrared temperature detector.

#### Table 1

Thermal kinetics of the Claisen rearrangements in n-tetradecane

Entry	Temp (°C)	$k (\times 10^{-3}) (\min^{-1})$	
		For ANE	For AME
1	180	0.21±0.01	0.80±0.01
2	195	0.61±0.03	$1.78{\pm}0.04$
3	200	0.77±0.01	$2.25 {\pm} 0.04$
4	205	$1.02{\pm}0.03$	$3.02 {\pm} 0.10$
5	210	$1.39{\pm}0.04$	$3.68{\pm}0.02$
6	215	$2.05{\pm}0.06$	$4.54{\pm}0.07$

Table 2

Thermal kinetics of the Claisen rearrangements in NMP

Entry	Temp (°C)	$k (\times 10^{-3}) (\min^{-1}$	)
		For ANE	For AME
1	170	$0.64{\pm}0.02$	0.33±0.01
2	180	$1.02{\pm}0.03$	$0.54{\pm}0.02$
3	190	$1.49{\pm}0.07$	$1.08{\pm}0.04$
4	200	$2.13 \pm 0.09$	$2.07 {\pm} 0.05$
5	210	$2.85{\pm}0.07$	$3.88{\pm}0.10$



**Fig. 2.** Arrhenius plots of the rate and temperature data of rearrangements of ANE and AME in *n*-tetradecane at 180, 195, 200, 205, 210, and 215 °C. The activation energy Ea=115.2 kJ mol<sup>-1</sup> and the pre-exponential factor  $A=4.1\times10^9$  s<sup>-1</sup> for the rearrangement of ANE and the activation energy Ea=89.9 kJ mol<sup>-1</sup> and the pre-exponential factor  $A=1.9\times10^7$  s<sup>-1</sup> for the rearrangement of AME. See the Supplementary data for tabular data.

#### 2.1. MWI reactions in *n*-tetradecane

As can be seen in Table 3, three parallel experiments data show that there is a significantly temperature gradient between the effective temperatures of ANE and AME. Obviously, the observed temperature gradient is in accord with the model of Huang and Richert as the result of the selective heating. In the microwave transparent solvent, the MW energy couple with the polar solute (ANE), creating high thermal energy 'domains'. The temperature inside the domains is higher than the temperature of the bulk



**Fig. 3.** Arrhenius plots of the rate and temperature data of rearrangements of ANE and AME in NMP at 170, 180, 190, 200, and 210 °C. The activation energy Ea=70.1 kJ mol<sup>-1</sup> and the pre-exponential factor  $A=1.2\times10^5$  s<sup>-1</sup> for the rearrangement of ANE and the activation energy Ea=110.3 kJ mol<sup>-1</sup> and the pre-exponential factor  $A=3.1\times10^9$  s<sup>-1</sup> for the rearrangement of AME. See the Supplementary data for tabular data.

 Table 3

 MWI Reactions in *n*-tetradecane<sup>4</sup>

	2				1. 1.
Trial	$k (\times 10^{-3}) (\min^{-1})$		Effective	e T (°C)	T Gradient (°C) <sup>D</sup>
	ANE	AME	ANE	AME	
1	1.47±0.06	$1.67 \pm 0.04$	210	194	17
2	$1.74{\pm}0.05$	$1.64{\pm}0.06$	213	194	19
3	$1.61{\pm}0.05$	$1.59{\pm}0.09$	212	193	19

<sup>a</sup> Microwave setup: 180 °C, 300 W, Powermax off, stir high, constant temperature mode. Concentrations [ANE]=[AME]=0.1000 mol/L.

<sup>b</sup> T gradient is the temperature difference between ANE and AME.

solution. Notably, bulk solvent superheating (15  $^{\circ}$ C) was observed. This is possibly because of the flawed temperature measurement of the external infrared monitor, which was not calibrated, or the high output microwave power (300 W). No matter what the reason, this does not affect the conclusion because the reaction mixture is homogenous. This unique MW selective heating mechanism cannot be duplicated by convective heating process.

#### 2.2. MWI reactions in NMP

For the sake of strict comparison, the setups of MWI reactions in the solvent of NMP are the similar as those in the solvent of *n*tetradecane. The results of MWI reactions in NMP are shown in Table 4. As expected, the temperature gradient is decreased as the polarity of solvent increasing. Microwave absorbing solvent NMP increases the overall microwave absorbing ability of the bulk and simultaneously heats the molecules of AME and ANE, resulting in the decrease of the temperature gradient. Notably, a more significant superheating phenomenon was observed as well. In the constant temperature mode, the microwave initially applied high power to get the solution to the desired temperature at an appropriate rate. And then, the power decreases and maintains at a lower level to keep the temperature constant. The initial high output power may have a greater influence to the reaction mixture in NMP because of the strong microwave absorbing ability, resulting in a higher bulk temperature.

#### Table 4

MWI reactions in NMP<sup>a</sup>

Trial	$k(\times 10^{-3})(\min^{-1})$		Effective T (°C)		T Gradient (°C) <sup>b</sup>
	ANE	AME	ANE	AME	
1	3.60±0.08	4.13±0.04	214	212	2
2	$4.09{\pm}0.20$	$4.96{\pm}0.05$	218	215	3
3	$3.87{\pm}0.04$	$4.53{\pm}0.05$	216	214	2

<sup>a</sup> Microwave setup: 180 °C, 300 W, Powermax off, stir high, constant temperature mode. Concentrations [ANE]=[AME]=0.1000 mol/L.

<sup>b</sup> T gradient is the temperature difference between ANE and AME.

The above results reveal that microwave assisted reactions occur at higher temperature than the setup temperature, generally higher more than 10 °C, herein, even more than 35 °C for the Claisen rearrangement, an intramolecular first-order reaction. It can be seen from Tables 1 and 2 that the reaction constants increase two to three times if the reaction temperature increases 20°. On the other hand, microwave heating is more faster than the convention heating. Thus, overheating and fast heating are two of major reasons that accelerate the reactions under microwave irradiation conditions.

# 2.3. Influence of reactant concentration and microwave power on the temperature gradient

According to the mechanism of microwave dielectric heating, only the polar molecules selectively absorb microwave energy, nonpolar molecules cannot transform electromagnetic energy into heat. Therefore, it is considered that in nonpolar solvent *n*-tetradecane, the temperature gradient would increase when the concentration of ANE increases. So we performed the reactions at different concentrations in *n*-tetradecane with a newly calibrated microwave equipment. Although after new calibration the derived temperatures are different from previous ones even under the same reaction sets (data in Table 3 vs data in entry 1 in Table 5 and data in entry 4 in Table 6), our method need not determine exact absolute temperature, it determines temperature gradient. Thus, the results obtained in the newly calibrated microwave equipment do not impact our conclusion. The results are shown in Table 5. As we can see, the temperature gradients increase as the concentrations of the polar reactant ANE increase. The effective temperature of AME does not change when the concentration changes and is equal to the setup temperature. The observed tendency indicates that when the concentration of the ANE increases, there are more 'hot-spot' in the reaction mixture, resulting in higher effective temperature of ANE. Thus, greater temperature gradient was observed between ANE and AME

#### Table 5

MWI Reactions in *n*-tetradecane at different concentrations<sup>a</sup>

[M] <sup>b</sup> mol/L	$k (\times 10^{-3}) (\min^{-1})$		Effective T (°C)		T Gradient (°C) <sup>c</sup>
	ANE	AME	ANE	AME	
0.1000	0.82±0.04	1.31±0.03	201	189	12
0.2000	$1.12{\pm}0.06$	$1.48{\pm}0.08$	206	191	15
0.3000	$1.27{\pm}0.01$	$1.46{\pm}0.07$	208	191	17

 $^{\rm a}$  Microwave setup: 190 °C, 300 W, Powermax off, stir high, constant temperature mode. The data were obtained on a newly calibrated equipment.

<sup>b</sup> Concentration [M]=[ANE]=[AME].

<sup>c</sup> T gradient is the temperature difference between ANE and AME.

#### Table 6

MWI Reactions in *n*-tetradecane at different microwave powers.<sup>a</sup>

Power (W)	$k(\times 10^{-3})$ (min <sup>-1</sup> )		Effective T (°C)		T Gradient (°C) <sup>d</sup>
	ANE	AME	ANE	AME	
300 <sup>b</sup>	0.67±0.01	1.11±0.02	197	185	12
200 <sup>b</sup>	$0.44{\pm}0.02$	$0.87 {\pm} 0.05$	191	181	10
100 <sup>c</sup>	$0.86 {\pm} 0.02$	$1.35 {\pm} 0.03$	201	189	12
300 <sup>c</sup>	$1.27{\pm}0.01$	$1.46{\pm}0.07$	208	191	17
300 <sup>c</sup>	$1.27{\pm}0.01$	$1.46{\pm}0.07$	208	191	17

<sup>a</sup> Microwave setup: Powermax off, stir high, constant temperature mode. The data were obtained on a newly calibrated equipment.

<sup>b</sup> Concentration [ANE]=[AME]=0.1000 mol/L. Setup temperature 180 °C.

<sup>c</sup> Concentration [ANE]=[AME]=0.3000 mol/L. Setup temperature 190 °C.

<sup>d</sup> T gradient is the temperature difference between ANE and AME.

It should also be noted that the level of the microwave heating depends on the amount of microwave energy transmitted to the reaction mixture. So we next investigated the effect of microwave power on the reaction kinetics. MWI reactions at different microwave powers in *n*-tetradecane with a calibrated microwave equipment were performed. The results are summarized in Table 6. At power 300 W, the temperature gradient is 12 °C (Table 6, entry 1). The effective temperature of AME is 5 °C higher than the setup temperature, it may be the result of the high microwave power. Decreasing the power to 200 W, the temperature gradient slightly decreases to 10 °C and the effective temperature of AME is equal to the setup temperature (Table 6, entry 2). When the reaction was performed in 100 W, the reaction mixture cannot be heated to 180 °C. So, we increased the concentrations of ANE and AME to 0.3000 mol/L and performed the reactions at 100 W and 300 W with the setup temperature 190 °C (Table 6, entries 3 and 4). The results show that the temperature gradient increases when the microwave power increases.

#### 3. Conclusion

The current results indicate that microwave selective heating can be achieved in homogeneous organic reaction mixture, and that, the selective heating can result in a measurable temperature gradient among different polar reactants in reaction mixture under certain conditions, such as in nonpolar solvents. The concentration of the polar reactants and the microwave power affect the temperature gradient.

For homogeneous solution phase organic reactions, both the polarity of reactants and solvent play significant roles in microwave-assisted reactions. A polar solvent is necessary if the reactants are non-absorbing (nonpolar) for fast heating. The polar solvents couple very efficiently with the microwave energy, leading to a rapid rise in internal temperature of the reaction mixture synchronously. When the reactants are strong-absorbing, though nonpolar solvents do not couple well with microwave energy, reactions can be also accelerated by the microwave irradiation: excess heat will be produced from the direct interaction between polar reactants and microwave irradiation, and hence, accelerates the reaction while the average internal temperature remains low.

But the occurrence of microwave selective heating polar reactants in nonpolar solvent is little practical applications. The reaction mixture of nonpolar solvent needs a high microwave power and is heated really slow compared to that of polar solvent, the vast majority of microwave energy are wasted. In addition, the Claisen rearrangements we used in this study are typical intramolecular reactions, they can undergo the rearrangement within the domains without transmit heat to other reactants. Thus, obviously different temperature gradient is observed between different polar reactants. Our results also indicate that overheating and fast heating are two of major reasons that accelerate the reactions under microwave irradiation conditions.

#### 4. Experimental section

#### 4.1. General information

Melting points were determined on a Yanaco MP-500 melting point apparatus and are uncorrected. All <sup>1</sup>H (400 MHz) and <sup>13</sup>C NMR (101 MHz) spectra were recorded on a Bruker 400 NMR spectrometer in CDCl<sub>3</sub> with TMS as an internal standard and chemical shifts are reported in ppm. All coupling constants (J) in <sup>1</sup>H NMR are absolute values given in hertz (Hz) with peaks labeled as single (s), broad singlet (br), doublet (d), triplet (t), quartet (q), and multiplet (m). Column chromatography with silica gel (200–300 mesh) was carried out with petroleum ether (PE, 60 °C–90 °C) and ethyl acetate (EA) as the eluent. *n*-Tetradecane (J & K), *N*-methylpyrrolidone, 4-methylphenol, 4-nitrophenol, and allyl bromide (J & K) were obtained commercially and used as received.

# 4.2. General procedure for preparation of allyl 4-substituted phenyl ethers

Allyl aryl ethers were synthesized following the established procedure.<sup>16</sup> 4-Substituted phenol (0.3 mol), allyl bromide (32 mL, 0.36 mol), potassium carbonate (50 g, 0.36 mol), and 100 mL of dry acetone were added in a 500 mL round-bottomed flask. The solution was refluxed for 6 h. After cooled, 500 mL of deionized water was added to the solution, which was then extracted twice with dichloromethane (50 mL). The extracted organic layer was washed three times with 30 mL of 5% w/w KOH solution (5 g of KOH/100 g water) and finally with deionized water. The organic layer was then dried over anhydrous sodium sulfate. After dichloromethane was evaporated using a rotary evaporator, the residue was distilled under reduced pressure or crystallized.

4.2.1. Allyl 4-nitrophenyl ether (ANE). After concentration at reduced pressure, the residue was recrystallized in a mixture of toluene and petroleum ether in an ice-water bath to afford light yellow crystals, mp 27–28 °C. <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  8.20 (d, *J*=9.3 Hz, 2H), 6.97 (d, *J*=9.3 Hz, 2H), 6.05 (ddd, *J*=22.5, 10.5, 5.3 Hz, 1H), 5.44 (dd, *J*=17.3, 1.3 Hz, 1H), 5.35 (dd, *J*=10.5, 1.2 Hz, 1H), 4.64 (d, *J*=5.3 Hz, 2H). <sup>13</sup>C NMR (101 MHz, CDCl<sub>3</sub>)  $\delta$  163.6, 141.6, 131.9, 125.9, 118.6, 114.7, 69.4.

4.2.2. Allyl 4-methylphenyl ether (AME). After concentration at reduced pressure, the residue was purified by reduced pressure distillation to afford clarity liquid at 68–69 °C/0.04 MPa; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  7.07 (d, *J*=8.5 Hz, 2H), 6.81 (d, *J*=8.4 Hz, 2H), 6.05 (ddd, *J*=16.5, 10.5, 5.3 Hz, 1H), 5.39 (dd, *J*=17.3, 1.4 Hz, 1H), 5.26 (dd, *J*=10.5, 1.2 Hz, 1H), 4.50 (d, *J*=5.3 Hz, 2H), 2.28 (s, 3H). <sup>13</sup>C NMR (101 MHz, CDCl<sub>3</sub>)  $\delta$  156.4, 133.5, 129.9, 129.8, 117.3, 114.5, 68.8, 20.4.

#### 4.3. General procedure for preparation of 4-substituted 2allylphenols

4-Substituted 2-allylphenols were synthesized by the Claisen rearrangement of allyl 4-substituted phenyl ethers. A solution of an allyl aryl ether (4-nitrophenyl ether (537 mg, 3 mmol) in 4 mL of tetradecane or 1 mL of pure allyl 4-methylphenyl ether) was stirred at 220 °C for 4 h under microwave irradiation in a sealed vessel. The reaction mixture was cooled and extracted with saturated sodium hydroxide solution. The combined basic solution was washed twice with dichloromethane, and then acidified to pH=1 with concentrated hydrochloric acid. The resulting mixture was extracted three times with dichloromethane. The combined organic phase was dried over anhydrous sodium sulfate. After concentration at reduced pressure, the residue was purified by silica gel column chromatography with ethyl acetate and petroleum ether (1:5, v/v) as eluent.

4.3.1. 2-Allyl-4-nitrophenol. White solid, mp 82–83 °C, lit.<sup>16</sup> mp 79.0–79.6 °C. <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  8.11–8.05 (m, 2H), 6.92 (d, *J*=8.6 Hz, 1H), 6.37 (s, 1H), 6.01 (ddt, *J*=16.7, 10.2, 6.5 Hz, 1H), 5.27–5.15 (m, 2H), 3.47 (d, *J*=6.5 Hz, 2H). <sup>13</sup>C NMR (101 MHz, CDCl<sub>3</sub>)  $\delta$  160.0, 141.3, 134.6, 126.8, 126.3, 124.2, 117.8, 115.7, 34.4.

4.3.2. 2-Allyl-4-ethylphenol. Colorless liquid; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  6.92 (d, *J*=6.9 Hz, 2H), 6.70 (d, *J*=8.7 Hz, 1H), 6.01 (ddt, *J*=16.8, 10.4, 6.3 Hz, 1H), 5.23–5.05 (m, 2H), 4.83 (s, 1H), 3.37 (d, *J*=6.3 Hz, 2H), 2.25 (s, 3H). <sup>13</sup>C NMR (101 MHz, CDCl<sub>3</sub>)  $\delta$  151.8, 136.5, 130.9, 130.1, 128.2, 125.0, 116.3, 115.6, 35.1, 20.4.

#### 4.4. Kinetic studies

10 mL of reaction mixture (0.1 M of AME and ANE, 100 mg naphthalene) reacted under microwave or thermal conditions. At

a periodic time, 0.1 mL of sample was taken out by a syringe with long needle. The samples were added into 1 mL of acetonitrile and then diluted to 20 times before analyzing by HPLC. The concentrations of ANE and AME present in reaction mixture were determined by means of HPLC. Measurements were made on Agilent 1100 HPLC equipped with a C18 chromatographic column ( $250 \times 4.6$  mm) with an eluent of acetonitrile:H<sub>2</sub>O (60:40, v/v) at a flow rate of 1 mL/min. UV detection wavelength was 254 nm. Injection volume was 10 µL. To calibrate the HPLC response to the concentrations of allyl 4-nitrophenyl ether and allyl 4-methylphenyl ether, a curve was constructed by analyzing a series of standard concentrations of each compound dissolved in acetonitrile by HPLC with naphthalene as internal standard (Figs. S9 and S10).

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#### Supplementary data

Supplementary data related to this article can be found, in the online version at http://dx.doi.org/10.1016/j.tet.2016.07.041. These data include MOL files and InChiKeys of the most important compounds described in this article.

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