# Parameters Affecting the Microwave-Specific Acceleration of a Chemical Reaction

Po-Kai Chen, Michael R. Rosana, Gregory B. Dudley, and A. E. Stiegman*

Department of Chemistry and Biochemistry, Florida State University, Tallahassee, Florida 32312, United States

S *Supporting Information*

ABSTRACT: Under appropriate conditions, significant microwave-specific enhancement of the reaction rate of an organic chemical reaction can be observed. Specifically, the unimolecular Claisen rearrangement of allyl *p*-nitrophenyl ether (ApNE) dissolved in naphthalene was studied under microwave heating and conventional convective (thermal) heating. Under constant microwave power, reaching a temperature of 185 °C, a 4-fold rate enhancement was observed in the microwave over that using convective heating; this means that the microwave reaction was proceeding at an effective temperature of 202 °C. Conversely, under constant temperature microwave conditions (200 °C), a negligible (~1.5-fold) microwave-specific rate enhancement was observed. The largest microwave-specific rate enhancement was observed when a series of 300 W pulses, programmed for 145–175 °C and 85–155 °C cycles, where 2- and 9-fold rate enhancements, over what would be predicted by conventional thermal heating, was observed, respectively. The postulated origins of the microwave-specific effect are purely thermal and arise from selective heating of ApNE, a microwave-absorbing reactant in a nonabsorbing solvent. Under these conditions, excess heat is accumulated in the domains around the ApNE solute so that it experiences a higher effective temperature than the measured temperature of the bulk medium, resulting in an accelerated unimolecular rearrangement.
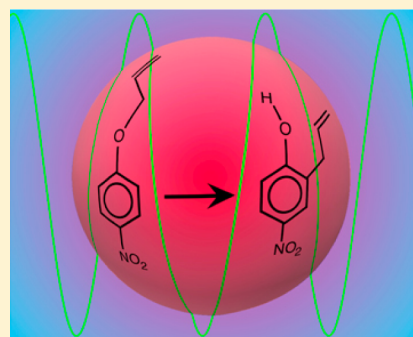
INTRODUCTION

The existence of microwave-specific enhancements to the rates of homogeneous organic chemical reactions, which have no counterpart in conventional convective heating, has been debated since it was first suggested. The hypothesis of such an effect is based on reported rates of reaction under microwave irradiation that exceeded what could be achieved by conventional convective heating under isothermal conditions.[1−8] However, many such reports were incorrect due to the fact that the temperatures measured in the microwave cavity were markedly in error, and when accurate values were obtained, it was found that the reaction rates were indistinguishable from those of the reactions run at that same temperature with convective (thermal) heating.[9−12] In addition to experimental errors, a common postulate for the origin of microwave-specific rate enhancement was a suggested non-thermal coupling of the radiation with molecules in solution to reduce, among other things, the activation energy of the reaction.[13] The nonthermal hypothesis, while still appearing in the literature, is highly improbable, largely because there are no obvious, quantum mechanical mechanisms by which radiation at the very low energies provided by the microwave can couple resonantly with a molecule in such a way that a bond-breaking or -making process can be accelerated. Most of these arguments were thoroughly addressed in a pair of papers by Stuerga published earlier.[14] In fact, so pervasive has been the dismissal of both experimental and theoretical claims of microwave effects that a view commonly held in the synthetic organic community is that there are no microwave-specific effects of any kind in homogeneous reactions, because "heat is heat" regardless of how it is generated.[15,16] Such generalizations and their specious aphorisms, however, ignore the basic physics of microwave heating, which is fundamentally different from convective heating. Unlike convective heating, heat is generated in the microwave from loss processes associated with coupling of the electromagnetic radiation to the dipole of individual molecules; this can, under the right circumstances, result in the selective heating of those molecules.[17−19] More specifically, if a highly absorbing molecule is present as a solute in a nonabsorbing solvent, then the heat gained by the entire solution (as determined by the measured temperature) must arise from convective heating of the solvent by the absorbing solute as it absorbs the radiation. Under steady-state conditions in which radiative heating of the absorber is followed by convective heat flow into the medium and, ultimately, out of the system, the effective temperature (i.e., accumulated heat) of the absorbing species will necessarily be, on average, higher than that of the solvent.[20−22] The existence of a differential in the effective temperature between an absorbing molecule and the bulk solution has been established by dielectric relaxation spectroscopy.[17,18] What has not been determined previously, however, is whether the magnitude of the accumulated heat is sufficient to realize a measurable enhancement in the reaction

rate. In this study, we report direct observation of microwave-specific rate enhancement for the unimolecular aryl Claisen rearrangement of allyl *p*-nitrophenyl ether in a nonpolar solvent.

■ RESULTS AND DISCUSSION

The conversion of absorbed microwaves into heat in a dielectric (i.e., nonconductive, nonmagnetic) material is described macroscopically through the dielectric continuum model.[19,23,24] In this treatment, the bulk permittivity of a material, ε, is expressed in its complex form, as given in eq 1, where ε' is the real component, which is the dielectric constant in the case where there is no absorption and which varies when absorption is taking place (anomalous dispersion).

$$\varepsilon = \varepsilon' - i\varepsilon'' \tag{1}$$

The complex component, ε'', characterizes the dielectric loss. Both the real and imaginary components of bulk permittivity are frequency-dependent, with the real component representing the transmission of the radiation through the material and the complex component representing its absorption. Energy dissipation in a dielectric medium depends on the relative magnitude of the real and imaginary dielectric constant; it is often quantified by the loss tangent given by eq 2.

$$\tan \delta = \varepsilon''/\varepsilon' \tag{2}$$

For a molecule in solution, the loss processes that lead to heating are most often understood in terms of Debye theory: coercion of the molecular dipole by the electric field of the radiation leads to energy loss that is often viewed as a frictional heating process in the medium.

The flow of energy that can potentially give rise to the selective heating of a dipolar molecule in a nonabsorbing medium, which was described in recent studies by Huang and Richert,[17,18] is shown schematically in Figure 1. In this model, a dipolar molecule is solvated by a nonabsorbing solution, creating a "domain" within which heat is generated by the microwave through Debye-type loss processes. It is the amount of energy absorbed and accumulated by the domain, above that of the medium, which can potentially lead to microwave-specific rate enhancement. As indicated in Figure 1, the microwave energy of intensity, I, is absorbed by the dipolar molecule with an efficiency that is dictated by the absorption cross-section (α) of the domain at the applied frequency (2.45 GHz). The efficiency of this absorption process will depend both on the properties of the dipolar molecules and the nature of the solvation sphere around it. The bulk medium is then heated by the convective heat flow from the domains ($g_c(T^{dom} - T^{med})$), which is a function of the difference between the effective temperature (i.e., heat) in the domains and that of the surrounding solvent medium. The excess heat accumulated in the domain ($T^{dom} > T^{med}$) will depend on the efficiency of convective heat transfer into the medium. A fundamental aspect of microwave heating that distinguishes it from conventional heating is that this transfer process, while being highly system-dependent, can be slow, analogous to configurational modes that can relax their excess energy much slower than what is expected on the basis of thermal conductivity. In short, the accumulation of excess heat in the domains occurs when there is a mode involved that absorbs energy at a rate faster than it can transfer it to the solvent (i.e., there is a small convective heat transfer coefficient, g_c).[25] For a large number of systems, this will not be the case; for example, systems in which all
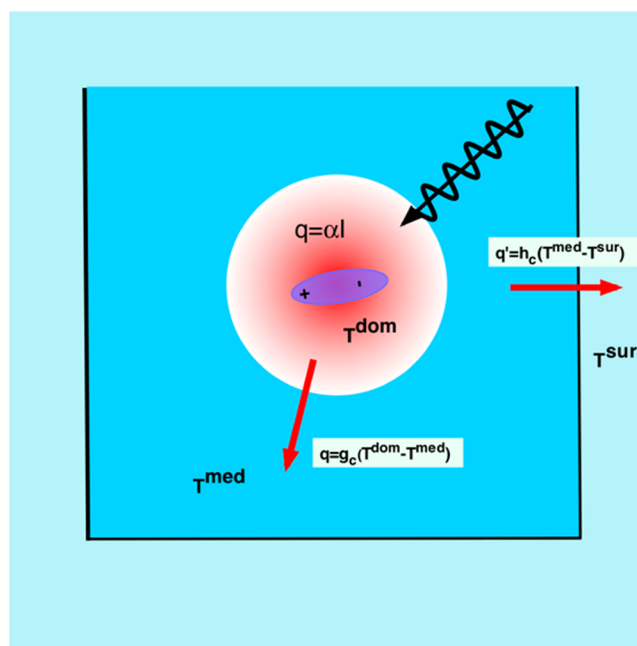

Figure 1. Energy transfer in the system in which a microwave-absorbing molecule is dissolved in a nonabsorbing solvent. I is the intensity of the microwave radiation, α is the molar absorption cross-sections of the molecules at 2.45 GHz, T^{dom} is the effective temperature of the domain, T^{med} and T^{sur} are the temperature of the medium (solvent) and the surroundings, and g_c and h_c are the convective heat transfer coefficients between the domain and the medium and between the medium and its surroundings, respectively.

constituents are strongly microwave-absorbing, such as pure polar liquids or reactions run in a polar solvent, are unlikely to exhibit a microwave-specific effect, because $T^{dom} - T^{med}$ is likely to be small. Similarly, completely closed systems that retain a large amount of heat throughout may also obscure any microwave-specific heating effects. For the ApNE reactant, the translational and vibrational modes of the molecule that lead down the reactive channel to products are populated thermally from within the domains and not through resonate absorption of the radiations, which is far too low in energy.

Optimization of the Reacting System for Microwave Absorption. Working within the parameters described above of an absorbing reactant in a nonabsorbing solvent, we wished to select a system in which the absorption of microwave radiation is maximized. Optimizing the microwave heating profile is likely a necessary, although perhaps not sufficient, condition to ensure detectable heat accumulation differentials. A unimolecular reaction such as an aryl Claisen rearrangement was considered likely to be suitable as a probe reaction because it can undergo rearrangement within the domains at a rate that will be dictated by the effective temperature that the molecule experiences. In addition, the reaction is typically clean and follows simple first-order kinetics, so it is easy to obtain reliable rate constants and Arrhenius parameters for use in comparing the thermal (convectively heated) and microwave reactions. Microwave-driven Claisen rearrangements have been reported previously; however, in most of these studies, the reaction was either carried out in an absorbing solvent or some other mechanism was used to intercept the microwave radiation and convert it secondarily to heat. As such, microwave-specific thermal effects would be unlikely to be observed.[26–31] An exception to this, which will be discussed later, is the study by

Durand-Reville et al., where an enhanced yield for a Claisen rearrangement was observed under the specific condition that the microwave radiation was applied as a series of 15 s pulses.[32]

Of the molecular properties predicted by the Debye equation to affect the magnitude of the loss tangent, one of the most pronounced is the dipole moment. For the case of a dipolar molecule dissolved in a nonpolar solvent, ε'' is proportional to the square of the dipole moment.[23,33] As such, the prototypical aryl Claisen rearrangement substrate is allyl phenyl ether (APE) (cf. eq 3), which has a small dipole moment ($\mu = 1.31$ D) and,

(3)

APE
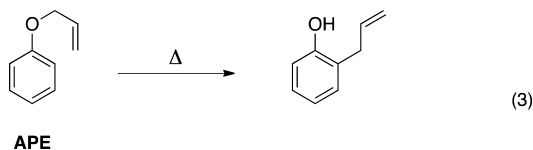
when dissolved in a nonabsorbing solvent, heats poorly. This can be seen in Figure 2a, where a 0.1 M solution of APE dispersed in mesitylene under 50 W irradiation remained below 40 °C even after 13 min of irradiation.

In order to increase the microwave absorption cross-section, we synthesized allyl *p*-nitrophenyl ether (ApNE) (eq 4), which

(4)

ApNE   **ANP**
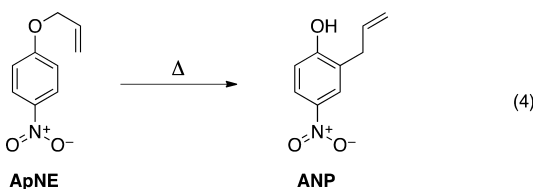
has a significantly larger dipole moment ($\mu = 5.68$ D) due to donor−acceptor interactions brought about by the strong electron-withdrawing group para to the oxygen.[34,35] As can be seen in Figure 2a, when dissolved in mesitylene (0.1 M, 50 W), a significant rate of heating was observed, particularly when compared to that of APE.

In addition to optimizing the dipole moment, properties of the solvent, such as viscosity and heat capacity, can play a role in the amount of energy absorbed. Because the reaction occurs at relatively high temperatures, a high-boiling, nonpolar, nonabsorbing solvent in which the ApNE is soluble is desirable. Heating curves at 50 W of microwave power of 0.1 M ApNE

solutions in three such solvents, *n*-decane, mesitylene, and naphthalene, are shown in Figure 2b. These solvents show little or no microwave heating in their pure forms, but strong heating was observed when ApNE was dissolved in them (Figure 2b). Moreover, the heating rate and the temperature at which steady-state conditions were obtained varied significantly for the three solvents.

The steady-state temperature attained for each solvent was, in descending order, naphthalene (169 °C) > mesitylene (154 °C) > *n*-decane (134 °C). ApNE dissolved in naphthalene was found to have the highest microwave absorption cross-section for heating to the solution temperatures required for this study. While naphthalene was a somewhat unorthodox choice (it is only liquid above ∼80 °C), we found that it worked extremely well for our investigation.

Finally, we note that in this study we compared reactions run in the microwave with reactions under conventional convective heating. While it is understood that the reactions were inherently driven by thermal processes in either setting, the two different heating methods will be differentiated as "microwave" and "thermal" in the text.

Thermal Reaction. The thermal reaction was carried out in a microwave-compatible reaction vessel (for direct comparison with the microwave reaction) in a temperature-controlled oil bath. The temperature was measured by a calibrated thermocouple and maintained to within ±1.0 °C using a thermostatically controlled oil bath. The disappearance of ApNE was measured as a function of time at four different temperatures between 200 and 215 °C in 5 °C increments over a period of 120 min. The extent of reaction at the end of the reaction time was 25.9% at 200 °C and 48.7% at 215 °C, as determined by GC analysis. Kinetic data were also collected at 185 °C, a low temperature for this reaction, for comparison with certain microwave experiments. The time required to collect a statistically meaningful set of concentration versus time data at that temperature was 480 min; the extent of reaction at the end of the determination was 20.3%. The plot of the natural log of the concentration of ApNE versus time at each temperature followed the expected first-order kinetics (Supporting Information, section 4).

For each temperature, four independent kinetic runs were conducted, and a first-order rate constant was obtained for each trial through a least-squares fit of the data; the final rate
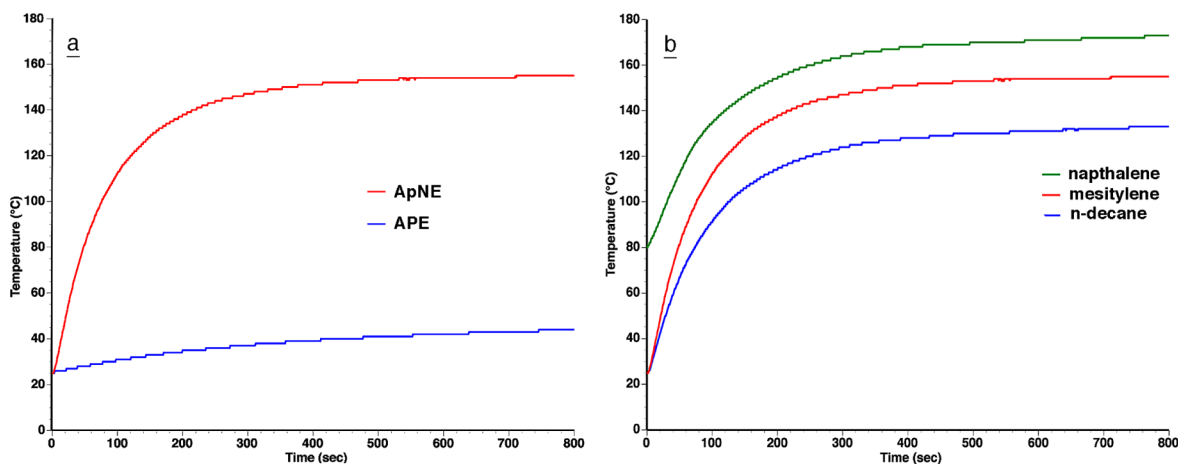
Figure 2. (a) Microwave heating curves of 0.1 M allylphenylether and allyl *p*-nitrophenyl ether in mesitylene at 50 W of applied microwave power; (b) microwave heating curves of 0.1 M allyl *p*-nitrophenyl ether in *n*-decane, mesitylene, and naphthalene under 50 W of applied microwave power.

constant plotted for each temperature was the average of the rate constants for the four independent trials (Supporting Information, section 4, Figure S6 and Table S2).

To determine the parameters of the Arrhenius equation, the rate constants were fit to the logarithmic form (Figure 3), yielding an activation energy for this Claisen rearrangement of $E_a = 151.1 \pm 1.2$ kJ mol^{-1} with a pre-exponential term of $A = (8.30 \pm 3.7) \times 10^{13}$ s^{-1}.
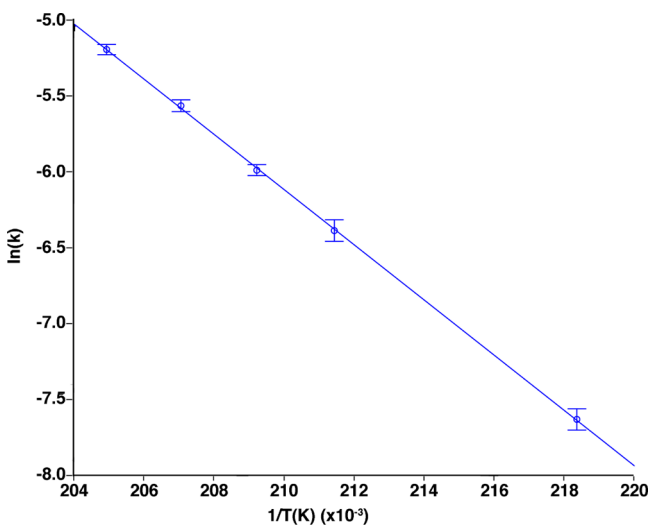

Figure 3. Arrhenius plot of the natural log of the rate constants as a function of the reciprocal of the absolute temperature.

Microwave Reactions. As discussed previously, there are a number of parameters that can potentially affect the amount of heat accumulated in the domains under microwave irradiation. For a fixed reaction system (solute and solvent), one of the most significant of those is the power, but exactly how power is applied will also be a factor in maintaining a significant temperature differential between the domains and the medium. Under conditions typically used in microwave chemistry, the reactions can be run as either closed (constant volume) or open (constant pressure) systems and, further, under constant temperature or constant power conditions. All of these parameters will have an effect on how heat is distributed in the solution and on the amount of excess heat that is accumulated in the domains. In this study, all reactions were done under open vessel (constant pressure) conditions and under either constant power or constant temperature conditions.

Constant Power Conditions. Two different concentrations of ApNE in naphthalene, 0.100 and 0.500 M, were irradiated at constant power, with the power for each concentration chosen to yield approximately the same temperature when steady-state conditions were met. The heating curve can be seen in Figure 4, where applied powers of 20 and 100 W were used for the 0.500 and 0.100 M solutions, respectively, to attain a steady-state temperature of ~185 °C. The heating curves followed the usual trajectory of microwave heating in that there was a rapid increase in temperature, and then, as steady-state conditions were reached, the temperature plateaued. The final temperature depended on the flow of heat from the absorbing molecules into solution and the convective heat flow out of the system. As such, there was some variability in the steady-state temperature depending on external factors, such as the temperature of the
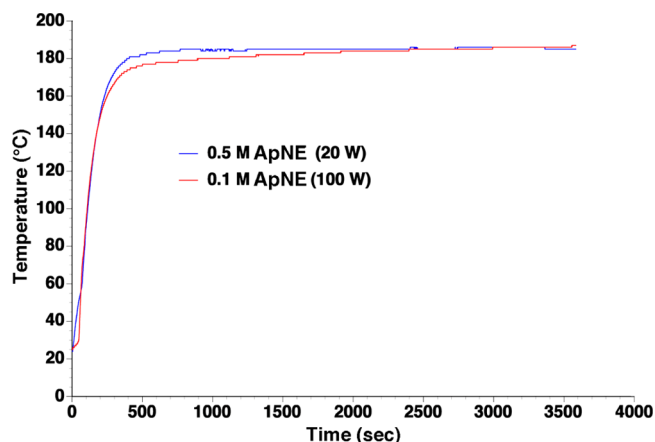

Figure 4. Heating curves for 0.1 and 0.5 M ApNE in naphthalene under constant power conditions.

surroundings and the rate of active cooling of the reaction container. For the heating curves, the temperatures were quite reproducible. For the 0.500 M solution at 20 W, we obtained an average final temperature for the three independent runs of 185.7 ± 1.0 °C. The average temperature over the entire curve was 178.7 °C, while over the plateau region, the average temperature between 500 and 4000 s was 185.0 °C. For the 0.100 M solution at 100 W, the final temperature was 187.2 ± 1.0 °C. The average over the entire heating curve was 176.5 °C, and the average over the range from 500 to 4000 s was 183.5 °C.

The disappearance of ApNE as a function of time is shown in Figure 5 (Supporting Information, section 8a). For the 0.500 M

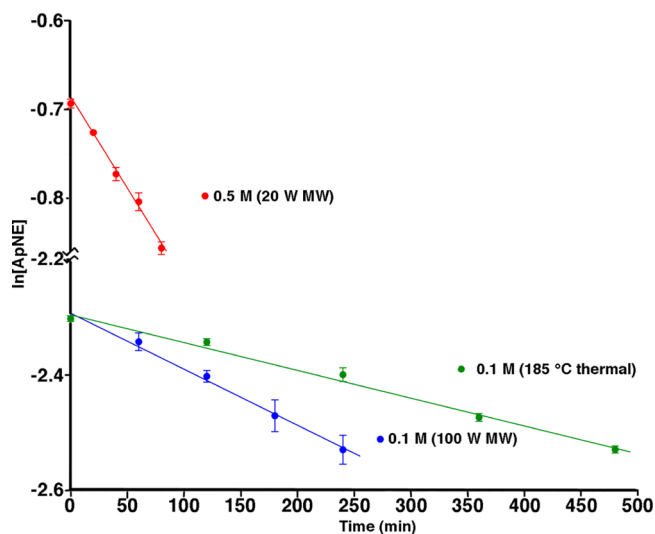**Figure 5.** First-order kinetics plot of the disappearance of ApNE under 20 and 100 W of microwave power and using convective heating at 185 °C.

ApNE under 20 W irradiation, the extent of the reaction over the 80 min reaction time was ~15%. The kinetics followed the first-order concentration dependence, and the rate constant, obtained from a least-squares fit of the ln[ApNE] versus time data, was found to be $(2.01 \pm 0.10) \times 10^{-3}$ min^{-1}. From the Arrhenius expression obtained for the thermal reaction and on the basis of the maximum temperature reached during the microwave run (185.7 °C), the thermal rate constant would be
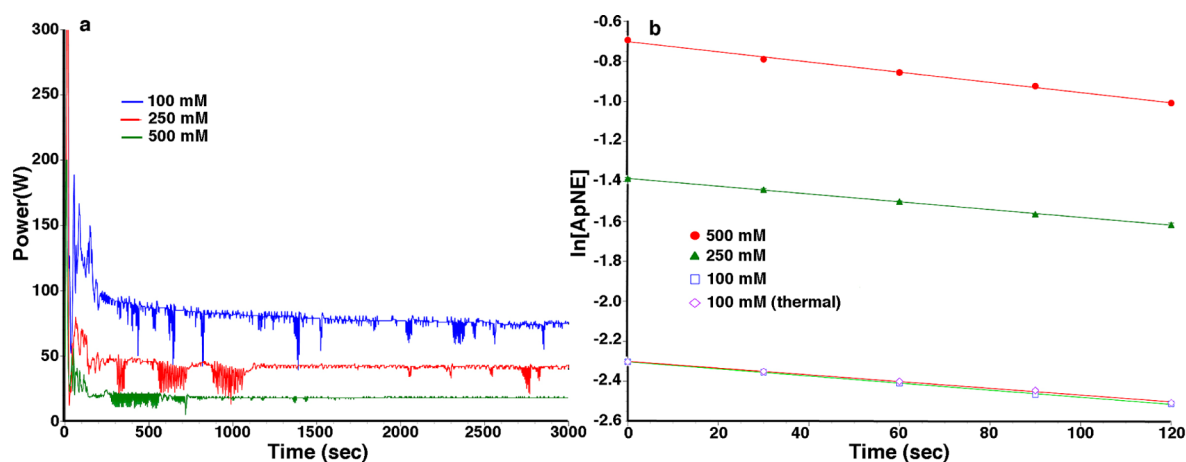
Figure 6. (a) Power applied by the microwave over time to maintain a constant temperature of 200 °C for 100, 250, and 500 mM solutions of ApNE in naphthalene; (b) kinetic plots of the decay of 100, 250, and 500 mM ApNE solutions in naphthalene at 200 °C under fixed temperature microwave conditions and convective heating at 200 °C for a 100 mM solution.

predicted to be no greater than $(5.14 \pm 2.75) \times 10^{-4}$ min^{-1}. The observed rate constant thus corresponded to a 3.9-fold rate enhancement from the use of microwaves to heat the reaction. Using the rate constant from the microwave reaction and the Arrhenius expression, the microwave-heated reaction rate was equal to what would be expected by heating conventionally at a temperature of 202 °C (assuming the activation energy was unchanged by the microwave), which is approximately 17 °C higher than the measured temperature of the medium.

To test the effects of absolute applied power on the magnitude of the microwave effect, we reduced the concentration of ApNE to 0.1 M so that, proportionally, more power (100 W) was required to reach the steady-state temperature of ~185 °C. Under these conditions, the disappearance of ApNE was found to be slower, requiring that the kinetic data be collected over a longer period of time (240 min). The decay of ApNE at this power showed first-order decay, yielding a rate constant of $(9.69 \pm 1.00) \times 10^{-4}$ min^{-1} (Figure 5). The Arrhenius expression predicted a thermal rate constant of $(4.84 \pm 2.59) \times 10^{-4}$ min^{-1} at this temperature, which suggested a relatively small, 2-fold, microwave-specific rate enhancement. The rate constant obtained in the microwave was equivalent to that for thermal heating at a temperature of 193.1 °C. A direct comparison of the first-order decay of a 0.1 M ApNE solution under conventional thermal and microwave conditions at 185 °C is shown in Figure 5.

Clearly, under constant power conditions there is an observable enhancement of the rate of reaction that can be unambiguously attributed to the use of microwave radiation. The observed concentration dependence on the degree of enhancement indicates that the microwave effect is neither directly related to the measured temperature of the medium (which is approximately the same in both experiments) nor is it dependent directly on the power. That the rate is only partially dependent on the measured temperature is consistent with the concept of excess heat accumulating in the domains around the absorbing dipole, the magnitude of which will depend on the properties of the solution. What is counterintuitive, however, is that we observed a higher rate using 20 W of power than using either 100 W or no microwave power. We had expected the amount of heat accumulated in the domains to increase with increasing applied power. This faster rate at 20 W (and higher

concentration) suggests that even though more radiation is being applied to the system the actual heat accumulated is smaller. This is unlikely, and a more probable origin of this this effect is due to changes in the properties of the solute−solvent system that take place when the composition was changed in order to attain a different power that reached the same steady-state temperature. In particular, reducing the amount of ApNE relative to the naphthalene solvent changes both the viscosity and heat capacity of the solution, with the former affecting the magnitude of the dielectric loss and the latter affecting the transfer of heat from the domains to the medium. In addition, as the concentration increases, there is the potential for aggregation of the dipoles into more complex domains containing more than one molecule, which will have different heat capacities and, potentially, different absorption cross-sections. Considerably more effort will be required to identify and comprehend the myriad subtle factors that must be considered for maximizing microwave-specific thermal effects on organic reactions.

Constant Temperature Microwave Heating. The use of constant temperature conditions in microwave-assisted organic synthesis is common and therefore it is of some interest to determine whether any selective microwave enhancement can be observed in this setting. In constant temperature mode, the microwave instrument automatically establishes and maintains a prescribed solution temperature using a dynamic feedback loop in which the power is varied in accordance with the measured temperature, which is detected by an internal fiber optic thermometer. The power required to maintain a fixed temperature in the reaction system will depend on the concentration of the ApNE, the efficiency of the convective heat transfer out of the domains, and the efficiency of heat transfer out of the reaction cell. As in the constant power case described above, a more dilute solution will require more power to maintain the temperature. This was observed experimentally: the power required to establish and maintain a constant temperature of 200 °C as a function of concentration is shown in Figure 6. As can be seen in the figure, the microwave initially applied high power to get the solution to the desired temperature. This initial stage was characterized by rapid and erratic power oscillations. After approximately 500 s and as the system equilibrated, the power decreased and became more

constant. The average power used, determined from 500–3000 s, was 18 W for 0.5 M, 41 W for 0.25 W, and 78 W for 0.10 M.

The disappearance of ApNE, maintained at 200 °C in the microwave, is shown in Figure 6b (Supporting Information, section 8b). The decay followed first-order kinetics; the rate constants and magnitude of the microwave enhancement over what would be predicted under thermal conditions are given in Table 1.

Table 1. Kinetic Parameters, Microwave Enhancement, and Effective Temperature for Constant Temperature Microwave Reactions

| [ApNE] (M)	$k \times 10^{-3}$ (min^{-1})	MW enhancement	effective T (°C)	$t_{1/2}$ (h)
0.100 (thermal)	1.68 ± 0.12	na	200.0 (actual)	6.9
0.100	1.78 ± 0.07	1.06	200.5	6.5
0.250	1.95 ± 0.22	1.16	201.7	5.9
0.500	2.55 ± 0.22	1.52	205.0	4.5

As can be seen, the magnitude of the microwave enhancement was minimal under constant temperature conditions, achieving no more than about a 1.5-fold rate constant enhancement over that of convective thermal heating and an effective thermal temperature that was only about 5 °C higher. The trend was toward greater microwave-specific rate enhancement at higher concentrations, even though the average applied power was lower, which paralleled that of the constant power experiments, ostensibly for similar reasons.

Pulsed Heating Conditions. In a recent report, enhanced reaction yields were observed under conditions in which the application of microwave energy was carried out in a series of pulses. Specifically, Durand-Reville et al. observed that for the Claisen rearrangement of a substituted propargylic enol ether into an azadirachtin precursor applying microwave power in a sequence of fifteen 1 min pulses (each pulse followed by a 90 s cool-down) produced a 17% higher (and more reproducible) yield than was realized from a single, 15 min, continuous irradiation.[32] Thermal reactions were comparatively ineffective. This is an intriguing result, as it suggests that there is a time dependence of the heat accumulation process, where the

effective ΔT between the domain and the medium may be larger during a dynamic heating process than it is when steady-state conditions are met.

To probe the nature and magnitude of this effect, we carried out a study of the ApNE Claisen rearrangement under pulsed microwave conditions. In these experiments, we carried out two independent studies in which we performed a series of heating–cooling cycles at a fixed microwave power of 300 W. In one study, the temperature was cycled over a temperature range from 85 to 155 °C, and in the other, over a temperature range from 145 to 175 °C. The reason for breaking the pulses over two temperature ranges was to determine how the effective temperature of the reactant in the microwave reaction changes along the temperature profile as the medium gets hotter. In the low-temperature experiment, the sample was pulsed to go from 85 to 155 °C and then cooled to 85 °C. This temperature range is generally below where any significant thermal reactivity will be observed during the typical reaction time of the experiment (the half-life of ApNE at 155 °C is 356 h). In the second experiment, the heating–cooling cycle was between 145 and 175 °C, which covered a higher temperature range, so more reactivity would have been expected (the half-life of ApNE at 175 °C is ~55 h). The heating curves for the two pulsed-temperature experiments over a 250 s period of time are shown in Figure 7. The 85–155 °C pulse occurred at a lower frequency due to the larger temperature excursion, with approximately 0.76 pulses per minute, compared to 1.4 pulses per minute for the 145–175 °C thermal pulses. The total reaction time for each pulse series and the number of pulses for each experiment over the reaction are given in Table 2.

As can be seen in Figure 7, the power was terminated by the microwave at the preset temperatures of 155 and 175 °C for the two experiments, but there was significant thermal overrun after each of the pulses. The actual peak temperatures attained were ~188 and ~200 °C, respectively. The amount of overrun was quite reproducible from pulse to pulse over the duration of the experiment, with average overruns of 30.5 ± 1.4 and 24.6 ± 0.6 °C, respectively, for the low-temperature (85–155 °C) and high-temperature (145–175 °C) ranges. The origin of the observed thermal overrun is not entirely clear. It may be attributable, at least in part, to instrumental factors, in particular the response time of the thermometer and the amount of time
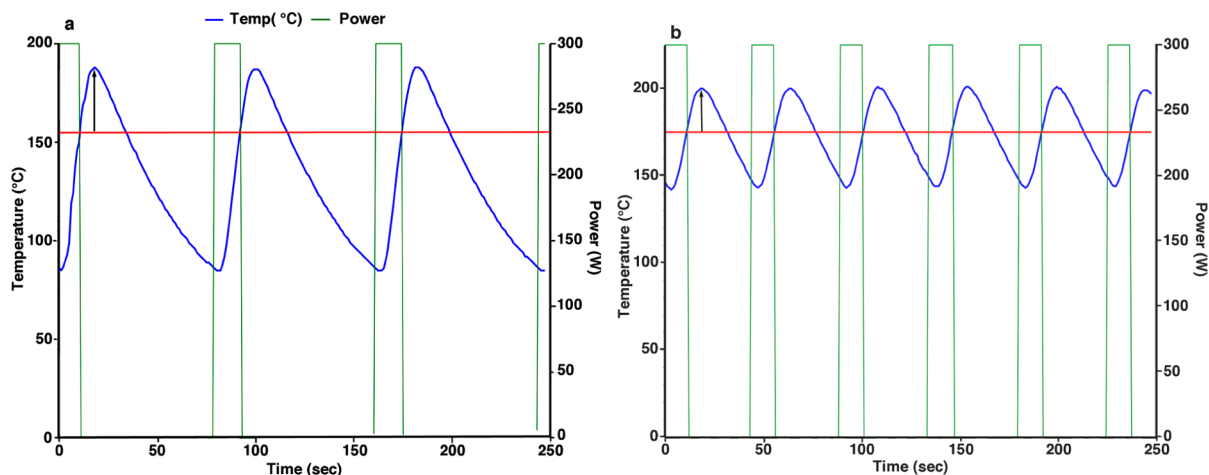
Figure 7. Temperature profile (blue line) and microwave power (green line) as a function of time for the (a) 85–155 °C and (b) 115–175 °C pulse series. The red line indicates the temperature where the system was set to turn off, and the vertical black arrow shows the degree of thermal overshoot above the preset temperature that occurred during the heating.

Table 2. Microwave Parameters, Effective Temperature, and Rate Constants for Pulsed Power Microwave Reactions

programmed temperature range (°C)	average measured temperature range (°C)	total reaction time (min)	total no. of pulses[a]	average temperature[a] (°C)	rate constant k ($\times 10^{-4}$ min^{-1})	effective thermal temperature (°C)[b]
85−155	85−188	420	320	130.3	7.05 ± 0.16	189.4
145−175	145−200	288	400	171.7	9.49 ± 0.42	192.9

[a]Over the duration of the reaction. [b]Obtained from the Arrhenius equation and the measured rate constants.

the magnetron took to cease emitting radiation after the shutdown command. However, the thermal overrun occurred over an 8−10 s time period, and it is unlikely that instrumentation lag would account more than a second of that. It is possible the thermal overrun represents the continuing release of heat from the domains after cessation of the radiation. Obviously, this suggestion requires further scrutiny; we will note, however, that the amount of overrun is dependent on the solvent used. Regardless of the origin of the thermal overrun, the temperatures actually obtained are included in all calculations used to compare thermal and microwave reactivity. Although we refer to the pulses by the programmed temperature range, it is understood that the actual range traversed will be considered.

The decay of ApNE under these pulse conditions (Figure 8) followed first-order kinetics (Supporting Information, section
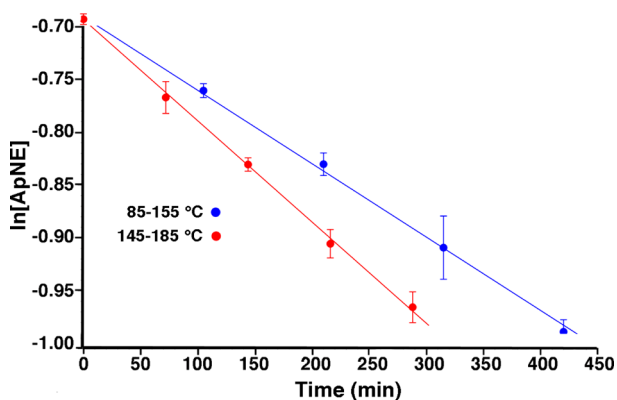

Figure 8. Kinetics of ApNE rearrangement under (blue) 85−155 °C and (red) 145−175 °C pulse series.

8c). Analysis of the decay data yielded rate constants for the 85−155 and 145−155 °C pulse conditions of k = (7.05 ± 0.16) × 10^{-4} and k = (9.49 ± 0.42) × 10^{-4} min^{-1}, respectively (Table 2). The effective temperatures required to realize these rate constants were T_{eff} = 189.4 °C and T_{eff} = 192.9 °C (Table 2). For comparison, the average measured temperatures over the duration of the experiment were T = 130.3 °C and 171.7 °C for the 85−155 °C and 145−155 °C pulse ranges, respectively.

The expected rate constants at the average temperatures of the two pulse experiments (130.3 and 171.7 °C) as determined from the Arrhenius expression were k = (0.0222 ± 0.0125) × 10^{-4} min^{-1} and k = (1.48 ± 0.90) × 10^{-4} min^{-1}, respectively (Table 3). This suggests a microwave-specific rate constant enhancement of 6.4-fold for the 145−175 °C pulse experiment and 320-fold for the 85−155 °C experiment. While at first glance these results suggest large microwave-specific effects, especially over the low-temperature range, the time-dependent temperature of the pulse experiments coupled with the fact that the rate constant was strongly temperature-dependent makes the comparisons using simply the measured average temperature far from meaningful.

We addressed more accurately and quantitatively the difference between the microwave and conventional thermal reaction under pulsed microwave conditions by determining the extent of the reaction that would be expected if the same temperature profile were produced using thermal pulses. This was done by calculating the expected extent of thermal reaction per pulse and summing over the total number of pulses to produce an expected thermal conversion and an integrated average temperature. To carry out this calculation, we first obtained the temperature as a function of time for the heating and cooling portions of the pulse by fitting the data to empirical equations. The functional relationship we obtained was then substituted into the Arrhenius equation to make it time dependent. The extent of reaction per pulse was subsequently determined from integrating the first-order rate equation, explicitly containing the time-dependent Arrhenius equation, over the duration of the pulse. The total extent of the reaction was calculated from the total number of pulses in each experiment (full details are given in the Supporting Information, section 3.3d). As can be seen in Table 3, when carried out thermally, the 145−175 °C pulse series was predicted to produce 12.0% reaction conversion over the 288 min duration of the experiment, which yielded an effective rate constant of k = 4.48 × 10^{-4} min^{-1} (i.e., the rate constant that would yield this extent of reaction over 288 min). This calculated expected rate corresponded to a thermal temperature of 184.1 °C, which was close to the measured average temperature of the microwave pulsed reaction and around 9 °C lower than the effective temperature of the substrate in the

Table 3. Comparative Thermal and Microwave Kinetic Results for Pulse Microwave Reactions

	MW pulse 85−155 °C	thermal 130.3 °C	thermal pulse 85−155 °C	MW pulse 145−175 °C	thermal 171.7 °C	thermal pulse 145−175 °C
extent of reaction (%)[b]	25.6[c]	0.093[c]	3.0[c]	23.9[d]	4.17[d]	12.0[d]
k ($\times 10^{-4}$ min^{-1})	7.05	0.0222	0.750[a]	9.49	1.48	4.48[a]
temperature (°C)	189.4	130.3	164.5	192.9	171.7	184.1
half-life (h)[e]	16.7	520.0	154.4	12.1	78.1	25.1

[a]Rate constant required to produce the predicted extent of reaction in minute. [b]Percent of ApNE converted to the 2-allyl-4-nitrophenol product. [c]420 min reaction. [d]288 min reaction. [e]First-order half-life $\tau_{1/2} = \ln(2)/k$.

microwave reaction. This result suggested a modest (~2-fold) microwave-specific rate enhancement and reduction of the half-life of the reaction. For the 85−155 °C pulse, the data suggested a much more dramatic effect. When carried out thermally, a 3.0% conversion was predicted over the reaction time, corresponding to an effective rate of $k = 7.50 \times 10^{-5}$ min^{-1} and an apparent temperature of 164.5 °C. This was well above the measured average temperature of the microwave reaction but 24.4 °C below the effective temperature of the substrate in the microwave reaction. The difference between calculated rate and the observed rate corresponded to a >9-fold microwave-specific rate enhancement and concomitant reduction in the half-life.

On the basis of the estimated reaction conversion if the processes were carried out thermally, it appears that using microwave pulse sequences does produce enhanced microwave effects. Moreover, it appears that the amount of microwave enhancement over what would be expected thermally is greater over the low-temperature (85−155 °C) pulse series, even though the overall rate is lower than in the high-temperature range. These results, however, are somewhat misleading. A more precise understanding of the microwave effect can be obtained by considering in more detail how microwave radiation is applied during the pulse experiment. In these experiments, the microwave reactor is irradiating the sample only during the heating cycle. As such, it is only during this period that there will be acceleration of the reaction due to a microwave effect. The extent of reaction that occurs during the cooling cycle will necessarily be purely thermal in nature. Using the calculation described above but only integrating over the cooling cycle, we found that the extent of the reaction occurring during the thermal cool-down stage of the pulses was 7.27 and 1.76% for the 145−175 °C and 85−155 °C pulse experiments, respectively. Using this, we could adjust the total reaction conversion to reflect only the contribution that occurs when the microwave is on. For the high-temperature range, the extent of the microwave portion of the reaction was 16.6%, and for the low range, it was 23.8%. Then, to estimate an effective rate constant during the microwave heating pulses, we needed to determine the time the reaction was actively heated by the microwave. For the 145−175 °C pulse, the average time that the microwave power was on per pulse was 11.1 ± 0.3 s, for a total of 74 min over the entire pulse series. The apparent rate constant was 24.5×10^{-4} min^{-1}, which yielded an effective temperature of 204.5 °C. For the 85−155 °C pulse, the average time the sample received microwave power was 12.5 ± 0.5 s per pulse, giving a total time of 66.7 min over the course of the reaction. This yielded an apparent rate constant of 40.8×10^{-4} min^{-1} and an effective temperature of 211.0 °C. The significance of these calculations is that they suggest that the effective temperature felt by the reacting molecules varies along the trajectory of the heating curve and is greater over the low-temperature range, particularly in view of the fact that the low-temperature range actually experiences less total exposure to the radiation.

The origin of the observed rate enhancement in the pulsed experiments can be understood from the dynamics of the heat absorption, accumulation, and transfer processes from the domains around the dipolar absorber. Specifically, as the dipolar molecule initially begins to absorb microwaves, heat accumulates in the domains more rapidly than it can be dissipated into the medium, leading to relatively high effective temperatures around the reactant. This slow dissipation of heat from the

domains to the medium arises from the fact that the frequency of the microwave radiation excites configurational modes in the dipole that relax slowly so that the direct transfer of heat to the rapid (predominantly vibrational) phonon modes of the medium is inherently inefficient (i.e., small convective heat transfer coefficient, g_c).[17,18] This is one of the fundamental factors that is expected to distinguish microwave heating from conventional heating. On the basis of the analysis given above, it appears that, at least for this system, the amount of excess heat accumulated in the domain is large at low temperatures and it decreases as the temperature of the medium increases. This suggests that, as the system heats and steady-state conditions are attained, the effective temperature difference will diminish and the accumulated energy will also reach a steady-state value. The magnitude of the steady-state value dictates the magnitude of the rate enhancement during a constant power experiment at steady state. The constant power experiment described previously for the 0.5 M solution, where the majority of the reaction takes place under steady-state conditions, has a smaller microwave effect on the observed rate, but it is also run at a lower applied power.

■ CONCLUSIONS

Taken together, the results of this study show that microwave-specific rate enhancements can be achieved in homogeneous organic reactions and that, under certain conditions, they can be pronounced. The observed rate enhancement can generally be rationalized from the model of Huang and Richert as arising from the selective heating of the dipolar reactant and concomitant accumulation of excess energy in the domains around the absorbing molecule. This mechanism is unique to the way in which microwave radiation heats molecules and has no parallel in conventional convective heating. Notably, this mechanism in no way involves any nonthermal effects, which, in our view, are highly improbable. One of the key results of our study is that the presence and magnitude of the microwave effect, in terms of the amount of rate enhancement that is attributable to the radiation, is highly variable; it depends profoundly on the manner in which the microwave radiation is applied. In particular, the use of constant temperature mode, in which the microwave adjusts the power dynamically to keep the solution at a constant temperature, produced the weakest microwave-specific effect for our system. This is particularly significant considering that constant temperature mode is perhaps the most common method by which microwave reactions are run. A more significant enhancement was observed under constant power mode, where the reaction was run at a fixed applied power. Under these conditions, our solutions reached and then maintained a steady-state temperature (~185 °C in our case) for the duration of the reaction. Notably, these two results indicate that it is meaningless to evaluate the existence of microwave effects run under constant power conditions by performing constant temperature measurements.[15,36] Using either constant temperature or constant power mode, the magnitude of the observed effect was concentration-dependent, with a larger effect observed for higher solute concentrations. The most significant enhancement we observed, however, was for pulsed microwave experiments in which we cycled through the early stages of microwave heating and repeatedly took advantage of the greater differences in solute effective temperature that seem to be possible at lower solution temperatures. It should be explicitly noted, however, that the study also indicates that the factors

that affect microwave enhancement are very complex and appear to be a delicate balance between microwave power, thermal properties of solution, and convective heat flow. This is evident in the power-dependent studies, which show that when we increase the power by changing the concentration, we actually get less reactivity.

The goal of this study was to quantify microwave-specific effects in a homogeneous organic reaction. In this and the preceding manuscript, we selected reaction systems with the objective of producing unambiguous results, without regard for synthetic utility. Importantly, our approach constitutes a more rigorous method for identifying and quantifying microwave effects. The method relies on first carrying out a complete kinetic analysis of the conventional thermal reaction from which the Arrhenius parameters can be determined. From the Arrhenius equation, and the kinetic results under microwave conditions we can determine the magnitude of any deviation from standard Arrhenius kinetics.

A pertinent question, however, is whether microwave-specific thermal effects can yield a practical advantage in organic synthesis. For the constant power reactions, the 0.5 M solution had a reaction half-life of 5.7 h in the microwave compared to 22.5 h thermally at the same temperature, suggesting that a useful advantage could be realized. Conversely, the constant temperature reaction gave a marginal microwave enhancement with a half-life for the 0.5 M solution of 4.5 h compared to 6.9 h thermally at 200 °C. Notably, the microwave-specific advantage diminished at lower concentrations in both methods. The most intriguing result, however, is the use of microwave-driven temperature pulses, which showed the largest rate enhancements and suggested a definitive advantage if there is a desire to keep the bulk solution temperature low. We also note that parameters that control the magnitude of a pulsed heating effect are far from understood, and, certainly, optimization of this process could potentially lead to large enhancements in reactivity. One approach to exploiting the pulse microwave effect may be to reduce the thermal contribution to the overall reaction by speeding up the cooling process through methods such as strong external cooling of the reaction vessel. Finally, the specific chemical system (reactant and solvent) will have a large effect on the magnitude of any microwave effect, suggesting that understanding and developing parameters for optimizing heat accumulation are likely to yield useful new microwave-specific processes. The system studied here was optimized for maximum microwave absorption by increasing the dipole moment of the absorbing species and through the choice of solvent. Among the strongest microwave absorbers are ionic compounds, which tend to be strongly absorbing at 2.45 GHz due to conductivity contributions to the dielectric loss in that frequency range.[37−41] In fact, recent studies from our laboratories were specifically designed to exploit the heating properties of ionic compounds, and significant microwave rate enhancements were observed.[42,43] Ionic inorganic complexes are often catalysts for organic transformations, and they are excellent candidates for realizing significant microwave enhancement.[44] In this regard, recent studies by Yamada et al. reported a very interesting microwave effect in a copper triflate-catalyzed Claisen rearrangement, in which rate was increased without a corresponding decrease in enantioselection.[45]

On the basis of the experiments, data, and observations described herein, we conclude that microwave-specific rate enhancements of homogeneous chemical reactions can occur

and that they arise from selective heating processes that arise from the unique manner in which microwaves interact with molecules in solution. The magnitude of the effects may be regarded as modest, but it seems clear that microwave-specific thermal effects can be observed and potentially exploited.

■ EXPERIMENTAL SECTION

Materials. Naphthalene (Aldrich, scintillation grade, ≥99%), mesitylene (≥99%), n-decane (≥99%), and allyl phenyl ether (99%) were obtained commercially and used as received. It should be noted that we specifically specify the producer and grade of naphthalene used because variations in source and grade were observed to affect the microwave reaction, presumably due to variations heat capacity.

Allyl p-Nitrophenyl Ether (ApNE). ApNE was synthesized following the established procedure for the synthesis of allyl phenyl ether.[46] 83.5 g (0.6 mol) of 4-nitrophenol (98%) was mixed with 63 mL (0.72 mol) of allyl bromide (99%), 100 g (0.72 mol) of potassium carbonate (>99.0%), and 200 mL of reagent grade acetone (>99.5%) in a 1000 mL round-bottomed flask. The solution was refluxed for 6 h and then allowed to stand overnight at room temperature. Deionized (DI) water (1000 mL) was added to the product solution, which was then extracted twice into dichloromethane (100 mL) (>99.5%). 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 for 30 min with 1 g of magnesium sulfate anhydrous (99.8%). The product was filtered, and the dichloromethane was evaporated using a rotary evaporator. The resulting product was a viscous liquid, which solidifies on standing in the freezer.

The product was subsequently purified by recrystallization. The crude product was dissolved in 100 mL of reagent grade toluene (99.5%), to which 0.5 g of activated charcoal was added for decolorization. The solution was filtered with through a medium frit packed with a layer of anhydrous magnesium sulfate. The filtered solution was then placed in rotary evaporator to remove approximately 80% of toluene. Petroleum ether (50 mL) was then added to concentrated solution, and it was placed in the freezer and allowed to precipitate. Once the precipitate was form, the mother liquor was decanted, leaving behind the product. The purified product was stored in a freezer to maintain its solid state, and the color of the precipitate was light yellow. Typical yield after two recrystallizations was about 12 g (11%). Characterization data matched previous reports.[46] Anal. Calcd for $C_9H_9NO_3$: C, 60.33; H, 5.06; N, 7.82. Found: C, 60.55; H, 5.07; N, 7.76. ^{1}H NMR (CDCl$_3$, 600 MHz) δ 8.13 (d, J = 9.2 Hz, 2H), 6.90 (d, J = 7.4 Hz, 2H), 6.00−5.94 (m, 1H), 5.38 (dd, J = 17.3, 1.3 Hz, 1H), 5.27 (dd, J = 10.5, 1.1 Hz, 1H), 4.57 (d, 2H) (Figure S1).

2-Allyl-4-Nitrophenol (ANP). ANP was synthesized by the Claisen rearrangement of p-nitro allyl phenyl ether. Neat allyl p-nitro phenyl (4 g) was heated at 220 °C in an oil bath for 15 min. The product was separated by column chromatography through high purity grade silica gel with a pore size of 60 Å and 200−400 mesh particle size. The column was prepared with a slurry of silica gel in hexane. The crude product was pipetted on the column and eluted with hexane to selectively remove the unreacted starting material. The product was subsequently eluted with dichloromethane. The product was collected after column chromatography, and the solvent was removed, leaving a yellow solid that was rinsed with warm hexane. Anal. Calcd for $C_9H_9NO_3$: C, 60.33; H, 5.06; N, 7.82. Found: C, 60.40; H, 5.14; N, 7.78. ^{1}H NMR (CDCl$_3$, 600 MHz) δ 8.00 (s, 1H), 7.99 (d, 1H), 6.83 (d, 1H), 5.97−5.90 (m, 1H), 5.65 (s, 1H), 5.19 (dd, J = 10.1, 1.3 Hz, 1H), 5.16 (dd, J = 17.2, 1.3 Hz, 1H), 3.41 (d, 2H) (Figure S2).

Methods. Solutions of ApNE of a specific concentration were made by weighing a sample of ApNE and then determining the volume of naphthalene that was required to reach the desired concentration. The mass of naphthalene required to give the requisite volume was calculated from the density of liquid naphthalene, which was determined experimentally to be 9.733 ± 0.002 g mL^{-1}.

The concentration of ApNE and ANP present in solution was determined by means of gas chromatography. Measurements were

made on a gas chromatograph equipped with a DB-5, nonpolar, low bleed, 5% phenyl-methylpolysiloxane, high-resolution gas chromatography capillary column with length of 30 m, i.d. of 0.32 mm, film thickness of 0.25 μm, and temperature limit of −60 to 325 °C. To optimize GC area for the column that was used, the gas flow rate of hydrogen to air was set at 1:10. For our analysis, we set the hydrogen flow rate at 30 mL/min and air flow rate at 300 mL/min. This corresponds to pressure reading from the gas tank of 20 psi for hydrogen and 70 psi for air. The carrier gas used for the analysis was helium at 20 psi. The detector type for the GC was flame ionization detector (FID) with a split-less injection. The injection and detecting temperature of the instrument were set at 250 °C. The temperature program for the analysis was as follows: 40 °C (hold 0 min), 5 °C/min to 70 °C (hold 1 min), 45 °C/min to 250 °C (hold 4 min), and 45 °C/min to 40 °C (hold 0 min).

To calibrate the GC response to the concentration of allyl *p*-nitrophenyl ether and 2-allyl-4-nitrophenol, a curve was constructed by analyzing a series of standard concentrations of each compound dissolved in toluene by GC. The calibration curves were generated by plotting the concentration against the integrated peak area. The concentrations of the solutions used were 0.015, 0.020, 0.030, 0.040, and 0.060 M for both compounds, and the area peak was determined by integrating the chromatogram. The instrument's response to both samples was linear (Figures S3 and S4). The concentration of ApNE and ANP was fit, using a linear regression analysis, as a function of the peak area (*A*) of the GC chromatogram (Equation S1). The intercept was forced through zero, consistent with zero concentration yielding zero peak area.

Samples of ApNE in naphthalene of known mass, reacted under either the microwave or thermal conditions, were dissolved in chromatographic grade toluene, to which 30 μL of *p*-xylene was added to serve as internal standard. Toluene was then added to the solution to achieve a total of 25 mL of solution in a volumetric flask. The solution was injected into the GC, and the integrated area of the peak corresponding to ApNE or ANP was determined using software specific to the instrument. The internal *p*-xylene reference was used to normalize the peak areas for differences in instrument response and variations in injection volume. The concentration was then determined from the calibration curve using Equation S1.

Thermometry. The temperature of the reaction was measured internally with a fiber optic thermometer that was interfaced with the microwave. The fiber optic thermometer was calibrated against a NIST traceable thermocouple accurate to ±0.001 °C. The average deviation over the temperature range studied was 0.55 °C, and the larges deviation observed was 1.2 °C.

Dipole Moment. The dipole moments for ApNE and APE were calculated using the Moeller−Plesset perturbation method (MP2), specifically MP2/6-311+G**.2.

Microwave Reactions. All microwave reactions were carried out in a CEM Discover SP microwave system. The reactor has a self-tuning, single-mode cavity, which allows for focused and consistent wattages to be supplied while eliminating any positional sensitivity or reflected power issues. The reactor is capable of supplying constant power in 1 W increments from 0 to 300 W. It has an automated power control so that a constant reaction temperature can be automatically maintained throughout the reaction. The microwave is equipped with an active sample cooling system that can be used to remove heat from the sample in a controlled manner. The reactor is capable of doing dynamic power cycling, whereby cycling between a specified high and low temperature can be performed at a fixed power. In this configuration, the power is on during the heating phase of the cycle and off during the cooling phase of the cycle.

The reaction vessel used for our experiment was a fabricated 10 mL quartz tube. A quartz vessel was used because it absorbs very little microwave radiation. This was confirmed experimentally. After 20 min of continuous 300 W of power applied to the empty quartz vessel, the temperature of the system increased by 1 to 2 °C. All reactions were run with a small magnetic stir bar that was placed in the quartz reaction vessel below the microwave field. Control experiments indicated that the stir bar made no significant contribution to the

heating of solutions in the sample cell because it resided at the bottom of the cell, out of the microwave field.

Microwave Power. Two identically equipped CEM Discover SP microwaves were used in the experiments. For both microwaves used in the study, the actual power present in the microwave cavity as a function of the applied microwave power (i.e., power set on the instrument) was determined over the range of powers using a protocol provided by the manufacturer. In the protocol, 50 mL of distilled water in a 100 mL round-bottomed flask is irradiated for 1 min at a fixed applied power. The actual power in the cavity is given by the equation P (W) = 6.97 $(T_f - T_i)$, where T_i and T_f are the initial and final temperature of the water. The applied and measured power for both microwaves is given in Table S1 and shown in Figure S5. The deviations between applied and actual power are relatively small over the power setting typically used in this study. Because of the better agreement between applied and actual power, all constant power experiments were carried out in microwave #2.

Kinetic Studies. To obtain kinetic data, under both microwave and thermal conditions, for the reaction of ApNE in naphthalene, four independent samples of the ApNE solution at the desired concentration were used for each reaction time. For example, for a reaction solution whose concentration was to be determined at 30, 60, 90, and 120 min in a kinetics run, four independent samples, withdrawn from the same stock solution of the desired concentration of ApNE in naphthalene, were reacted for 30 min, and the concentration of each was determined. Four fresh samples taken from the same stock solution were then reacted for 60 min, and the concentrations were determined; this procedure was repeated for the other time points. Once reacted, each of the samples was dissolved in toluene, diluted to 25 mL in a volumetric flask, and analyzed by GC. This was done to minimize the inherent difficulty in quantitatively withdrawing aliquots of a solution that solidifies rapidly when removed from the heat source. In addition, for the microwave studies, it removes the effect of cooling and then reheating with applied microwave power to reestablish the temperature that would result from trying to take multiple aliquots from the same sample.

Thermal Kinetics. The thermal reaction was carried out in an insulated mineral oil bath that was heated on a temperature-controlled hot plate with the temperature controlled to within 1 °C by an integrated controlled. The reactions were carried out in the same 10 mL quartz cells that were used in the microwave reaction. In the kinetic runs, the sample was inserted into the oil bath, which had been preheated to the desired temperature. Kinetic data was collected at five temperatures, 185, 200, 205, 210, and 215 °C. At each temperature, four independent rate determinations were made. Linearized (ln-[nAPE] vs time) first-order kinetic plots of the time-dependent concentration data collected at different temperatures were generated (Figure S6).

Rate Constants. The rate constants for each trial were the slope of the linearized first-order rate equations, determined from a linear regression. Results of the regression for all of the thermal kinetic data are given in Table S2, including the rate constant (*k*), its standard deviation (σ), the *R* factor for the regression, and the 95% confidence interval. The rate constant for each temperature used in the subsequent Arrhenius analysis was the average of the four trials for each temperature (Table S2), and the standard deviation of the average was calculated.

Arrhenius Analysis. The average rate constants determined at each temperature were fit to the linearized form of the Arrhenius equation. The plot of $\ln(k)$ vs $1/T$ (K) is linear (Figure S6a). Regression analysis was done using a least-squares fit in a commercial statistical program suite. Several linear regression techniques were evaluated to arrive at the best fit of the data, as judged by the residuals of the fit. The best statistics were obtained using a robust linear regression, the results of which are given in Table S2. The linear fit to the data was quite good, as evidenced by the R^2 factor, which was 0.9998, and the residuals (Figure S6b), which were never larger than 1%. Rate constants were calculated from the Arrhenius equation using the exponential form of the expression (Equation S3). The error in the calculated rate constants was derived by standard propagation of error (Equation S4).

The apparent thermal temperature, which is defined as the temperature at which a rate constant, k, obtained from a microwave reaction would be predicted thermally from the Arrhenius equation, is obtained from solving the Arrhenius equation for T, the absolute temperature (Equation S5).

Microwave Reaction Kinetics. The kinetics for allyl *p*-nitrophenyl ether (ApNE) were carried out by placing 3 mL of 0.100, 0.250, or 0.500 M of ApNE in naphthalene in the 10 mL quartz microwave tube. Temperature was monitored internally using a calibrated fiber optic thermometer. The fiber optic was held in place in the center of the reaction cell (and at the center of the cavity) by a cap, which was affixed to the top of the cell. The cap was vented and did not seal the cell so that the reactions were all run under constant pressure conditions. Kinetics data under microwave irradiation was obtained in the following manner. In a typical 2 h microwave reaction, four samples of the same ApNE concentration were used for each of the microwave irradiation times of 30, 60, 90, and 120 min. For example, for a 30 min reaction time, four independent samples were heated in succession in the microwave for 30 min, and the concentration of each was determined. For the 60 min reaction time, four new sample were irradiated and heated for 60 min. The same procedure was carried out for each time increment so that, for the four times from 30 to 120 min, 16 individual samples were used. There were a couple of reasons for this procedure. The first is practical. Because we are using naphthalene as a solvent, it is difficult to accurately extract a liquid aliquot from the vessel, as it will instantly solidify. Far more accurate concentration determination could be achieved by letting the entire sample solidify and then dissolving it for GC analysis. The second reason for using this procedure was so that all samples at each data point will experience the exact same initial application of microwave power and initial heating process. Each individual sample was allowed to solidify; it was then weighed and dissolved in chromatographic grade toluene to a fixed volume. The concentration of ApNE and ANP was then determined by GC analysis using the protocol described above.

Characterization of the Microwave Driven Claisen Rearrangement. The conversion of *p*-nitro allyl phenyl ether to allylphenol under microwave conditions was investigated by ^{1}H NMR spectroscopy. This experiment was carried out to determined if secondary products, not observed under thermal conditions, were produced in the microwave. The ^{1}H NMR spectrum of a 2 h (0.5 M, 60 W fixed power) microwave-driven reaction is presented in Figure S7. The reaction was carried out in perdeuteronaphthalene so that the reactant and product protons could be observed.

After irradiation, the only species observed in the ^{1}H NMR figure were the reactant, ApNE, and the product, ANP; no other secondary products or impurities were observed above trace levels. Specifically, in Figure S7, the integrated values for ApNE and ANP are labeled under their own chemical shifts and splitting patterns, which can be compared to the spectra for the pure compounds shown in Figures S1 and S2. Notably, the splitting pattern at δ 5.90 consists of contributions from both the product and reactant. The peaks that were not assigned an integration value were those of water (δ 1.35), CDCl$_3$ (δ 7.35), and deuterated naphthalene (δ 7.72, δ 7.88), which confirmed that in a 2 h microwave reaction there were no detectible side products generated in Claisen rearrangement of allyl *p*-nitrophenyl ether.

Mass Balance. To confirm that no significant mass loss occurs during the course of the reaction, we calculated the concentration of both the product and reactant as a function of reaction time, and we compared it with the initial concentration of reactant. The summation of the concentration of product and reactant should equal to the initial concentration of the reactant at all times. Figure S8 shows the ratio of the concentration of product plus the reactant divided by the initial convention of the reactant, expressed as a percent. Notably, the measured values of the concentration are all within 2.5% of the initial concentration, which is within experimental error for the determinations.

Microwave Kinetic Analysis. The kinetic data for all of the microwave experiments, determined from the disappearance of ApNE over time, was fit to a linearized first-order rate expression using a linear least-squares fit. The best statistics were obtained from regression fits to the average of the concentration of the four independent determinations at each time point. For all of the microwave experiments conducted, the results of the regression analysis, a graph of the data, the best-fit regression line, and the residuals, were determined.

Thermal Pulse Reaction Computation. To determine the extent to which a reaction would be expected if a pulse sequence was carried out over a temperature range for a specified number of pulses, we first obtained the temperature as a function of time, $T(t)$, for the heating and cooling portions of the pulse by fitting the data to empirical equations (Figure S12). The Arrhenius expression is substituted explicitly for the rate constant in the first-order rate equation and integrated (Equations S6−S8). The functional relationship $T(t)$ is then substituted into the integrated form of the equation. The extent of the reaction per pulse was subsequently determined from integrating the first-order rate equation (Equation S8), in two separate integration steps, over the time taken to heat and cool the reaction. The total extent of the entire reaction was calculated from the total number of pulses in each experiment (Equation S9).

■ ASSOCIATED CONTENT

⑤ Supporting Information

^{1}H NMR spectra, GC calibration curves, microwave cavity power calibration, mass balance verification, thermal and microwave kinetics plots, statistical analysis, and calculations. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*Tel.: 850-644-6605. Fax: 850-644-8281. E-mail: Stiegman@ chem.fsu.edu.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

■ REFERENCES

(1) Adnadjevic, B. K.; Jovanovic, J. D. *J. Mol. Catal. A: Chem.* **2012**, *356*, 70−77.

(2) Berlan, J.; Giboreau, P.; Lefeuvre, S.; Marchand, C. *Tetrahedron Lett.* **1991**, *32*, 2363−2366.

(3) Bose, A. K.; Manhas, M. S.; Banik, B. K.; Robb, E. W. *Res. Chem. Intermed.* **1994**, *20*, 1−11.

(4) Bose, A. K.; Manhas, M. S.; Ghosh, M.; Raju, V. S.; Tabei, K.; Urbanczyklipkowska, Z. *Heterocycles* **1990**, *30*, 741−744.

(5) Bougrin, K.; Bennani, A. K.; Tetouani, S. F.; Soufiaoui, M. *Tetrahedron Lett.* **1994**, *35*, 8373−8376.

(6) Gupta, R.; Gupta, A. K.; Paul, S.; Kachroo, P. L. *Indian J. Chem., Sect. B: Org. Chem. Incl. Med. Chem.* **1995**, *34*, 151−152.

(7) Srikrishna, A.; Nagaraju, S. *J. Chem. Soc., Perkin Trans. 1* **1992**, 311−312.

(8) Sun, W. C.; Guy, P. M.; Jahngen, J. H.; Rossomando, E. F.; Jahngen, E. G. E. *J. Org. Chem.* **1988**, *53*, 4414−4416.

(9) Jahngen, E. G. E.; Lentz, R. R.; Pesheck, P. S.; Sackett, P. H. *J. Org. Chem.* **1990**, *55*, 3406−3409.

(10) Laurent, R.; Laporterie, A.; Dubac, J.; Berlan, J.; Lefeuvre, S.; Audhuy, M. *J. Org. Chem.* **1992**, *57*, 7099−7102.

(11) Raner, K. D.; Strauss, C. R.; Vyskoc, F.; Mokbel, L. *J. Org. Chem.* **1993**, *58*, 950−953.

(12) Westaway, K. C.; Gedye, R. N. *J. Microwave Power Electromagn. Energy* **1995**, *30*, 219−230.

(13) de la Hoz, A.; Diaz-Ortiz, A.; Moreno, A. *Chem. Soc. Rev.* **2005**, *34*, 164−178.

(14) Stuerga, D. A. C.; Gaillard, P. *J. Microwave Power Electromagn. Energy* **1996**, *31*, 87−100.

(15) Kappe, C. O.; Pieber, B.; Dallinger, D. *Angew. Chem., Int. Ed.* **2013**, *52*, 1088−1094.

(16) *Microwave Heating as a Tool for Sustainable Chemistry*; Leadbeater, N. E., Ed.; CRC Press: Boca Raton, FL, 2011.

(17) Huang, W.; Richert, R. *J. Phys. Chem. B* **2008**, *112*, 9909−9913.

(18) Huang, W.; Richert, R. *J. Chem. Phys.* **2009**, *130*, 194509.

(19) Mingos, D. M. P.; Baghurst, D. R. *Chem. Soc. Rev.* **1991**, *20*, 1−47.

(20) de la Hoz, A.; Diaz-Ortiz, A.; Moreno, A. In *Microwaves in Organic Synthesis*; Loupy, A., Ed.; Wiley-VCH: Weinheim, Germany, 2006; Vol. *1*, pp 219−277.

(21) Hajek, M. In *Microwaves in Organic Synthesis*; Loupy, A., Ed.; Wiley-VCH: Weinheim, Germany, 2002; Vol. *1*, pp 345−374.

(22) Steinreiber, A.; Stadler, A.; Mayer, S. F.; Faber, K.; Kappe, C. O. *Tetrahedron Lett.* **2001**, *42*, 6283−6286.

(23) Metaxas, A. C.; Meredith, R. J. *Industrial Microwave Heating*; The Institution of Engineering and Technology: London, 1983.

(24) Stein, D. F.; Edgar, R. H. *Microwave Processing of Materials*; National Academy Press: Washington, DC, 1994.

(25) Khalife, A.; Pathak, U.; Richert, R. *Eur. Phys. J. B* **2011**, *83*, 429−435.

(26) Strauss, C.; Trainor, R. *Aust. J. Chem.* **1995**, *48*, 1665−1692.

(27) Baxendale, I. R.; Lee, A. L.; Ley, S. V. *J. Chem. Soc., Perkin Trans. 1* **2002**, 1850−1857.

(28) Gutmann, B.; Roduit, J.-P.; Roberge, D.; Kappe, C. O. *Angew. Chem., Int. Ed.* **2010**, *49*, 7101−7105.

(29) Lin, Y.-L.; Cheng, J.-Y.; Chu, Y.-H. *Tetrahedron* **2007**, *63*, 10949−10957.

(30) Nordmann, G.; Buchwald, S. L. *J. Am. Chem. Soc.* **2003**, *125*, 4978−4979.

(31) Razzaq, T.; Kremsner, J. M.; Kappe, C. O. *J. Org. Chem.* **2008**, *73*, 6321−6329.

(32) Durand-Reville, T.; Gobbi, L. B.; Gray, B. L.; Ley, S. V.; Scott, J. S. *Org. Lett.* **2002**, *4*, 3847−3850.

(33) Debye, P. *Polar Molecules*, 1st ed.; Chemical Catalog Company: New York, 1929.

(34) Graham, E. M.; Miskowski, V. M.; Perry, J. W.; Coulter, D. R.; Stiegman, A. E.; Schaefer, W. P.; Marsh, R. E. *J. Am. Chem. Soc.* **1989**, *111*, 8771−8779.

(35) Stiegman, A. E.; Miskowski, V. M.; Perry, J. W.; Coulter, D. R. *J. Am. Chem. Soc.* **1987**, *109*, 5884−5886.

(36) Dallinger, D.; Irfan, M.; Suljanovic, A.; Kappe, C. O. *J. Org. Chem.* **2010**, *75*, 5278−5288.

(37) Barthel, J.; Buchner, R.; Bachhuber, K.; Hetzenauer, H.; Kleebauer, M.; Ortmaier, H. *Pure Appl. Chem.* **1990**, *62*, 2287−2296.

(38) Barthel, J.; Feuerlein, F. *Z. Fur Phys. Chem. Neue Folge* **1986**, *148*, 157−170.

(39) Sutton, W. H. *Am. Ceram. Soc. Bull.* **1989**, *68*, 376−386.

(40) Wei, Y. Z.; Chiang, P.; Sridhar, S. *J. Chem. Phys.* **1992**, *96*, 4569−4573.

(41) Wei, Y. Z.; Sridhar, S. *J. Chem. Phys.* **1993**, *99*, 3119−3124.

(42) Rosana, M. R.; Tao, Y.; Stiegman, A. E.; Dudley, G. B. *Chem. Sci.* **2012**, *3*, 1240−1244.

(43) Rosana, M. R.; Hunt, J.; Ferrari, A.; Southworth, T. A.; Tao, Y.; Stiegman, A. E.; Dudley, G. B. *J. Org. Chem.* **2014**, DOI: 10.1021/jo501153r.

(44) Mehta, V. P.; Van der Eycken, E. V. *Chem. Soc. Rev.* **2011**, *40*, 4925−4936.

(45) Nushiro, K.; Kikuchi, S.; Yamada, T. *Chem. Commun.* **2013**, *49*, 8371−8373.

(46) White, W. N.; Gwynn, D.; Schlitt, R.; Girard, C.; Fife, W. *J. Am. Chem. Soc.* **1958**, *80*, 3271−3277.