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Direct Observation of the Molecular Structural Changes during the Claisen Rearrangement Including the Transition State

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The detailed processes in the Claisen rearrangement were observed. The process was vibrationally excited in the electronic ground state by a stimulated Raman process using a 5-fs pulse. The Claisen rearrangement was found to follow a three-step pathway. At first, the C^4–O bond is weakened to generate a bis-allyl-like intermediate. Next, the formation of a weak C^1–C^6 bond results in the generation of an aromatic-like intermediate. Finally, C^4–O breaking and C^1–C^6 formation occur simultaneously to generate the product.

The Claisen rearrangement (Figure 1) is one of the most useful and common sigmatropic rearrangements in organic synthesis known for its high stereoselectivity. [3,3]-Sigmatropic rearrangements of allyl aryl ethers reported by Claisen[1] helped spur the development of various other reactions.[2] The Claisen rearrangement is thought to proceed through a six-membered transition state (TS) by a supra–supra facial reaction following Woodward–Hoffmann rules[3] and frontier orbital theory.[4] Experimental stereochemical outcomes and theoretical calculations implicated a six-membered chair-form TS.[2e–2i] A more detailed mechanism of the Claisen rearrangement (Figure 1) was studied by theoretical calculations and the kinetic isotope effect (KIE) using allyl vinyl ether (AVE)[2a] in previous work.[5] As a result, a bis-allyl-like TS was suggested.[5e–5j] In this work, using a 5-fs laser pulse (Figures S1 in Supporting Information (SI)[6]) developed in our group,[7] we observed detailed molecular structural information in the molecular structure change states during rearrangement, including the TS,[8] via instantaneous vibration frequencies.[9]

AVE has an absorption peak located at a wavelength shorter than 220 nm, which cannot be reached either by one-photon or two-photon absorption of the visible 5-fs laser pulses (from 525 to 725 nm, Figure S1 in SI). At least three-photon absorption corresponding to the fifth-order nonlinearity is needed. Therefore, the 5-fs laser pulse triggers coherent molecular vibrations via the stimulated Raman process[10] corresponding to the third-order nonlinearity in the ground state.[11]

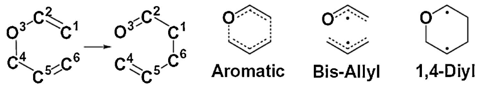

Figure 1. Three proposed TS. Aromatic like TS appears in a synchronous concerted case. Bis-allyl-like TS in which C^4–O bond breaking takes place in the first step of the reaction and 1,4-diyl-like TS in which C^1–C^6 bond formation takes place in the first step of the reaction appear in an asynchronous case.

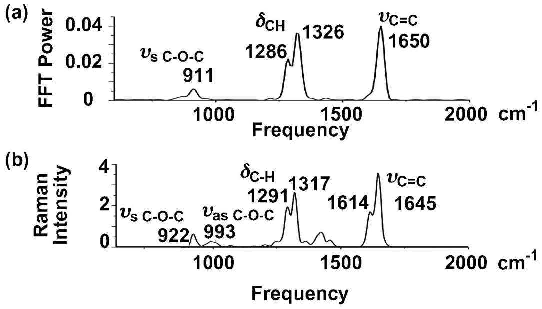

Figure 2. (a) FFT power spectrum of AVE. (b) Raman spectrum of AVE.

The induced absorbance difference ΔA oscillates around 0 within $\pm 5 \times 10^{-5}$, while the vibrational modulation ($\delta\Delta A$) is 3×10^{-4} (Figure S2 in SI). This indicates that there are no slow dynamics due to the excited electronic state population. The fast Fourier transform (FFT) power spectra of the real-time traces from 200 to 800 fs (Figure 2a) agree well with the Raman data of AVE (Figure 2b), which confirms that the pump–probe observations closely reflect molecular vibration dynamics of the electronic ground state. These observed frequencies can be assigned to the C=C stretch ($\nu_{\mathrm{C=C}}$) of the allyl and vinyl groups (1650 cm^{-1}), C–H deformation ($\delta_{\mathrm{C\text{–}H}}$) of the allyl and vinyl groups (1286 and 1326 cm^{-1}, respectively), and the C–O–C symmetric stretch ($\nu_{\mathrm{s\,C\text{–}O\text{–}C}}$) of the ether group (911 cm^{-1}).

A spectrogram[12] was obtained by time-gated Fourier transform with a Blackman window of 400 fs-FWHM (Figure 3). In the spectrogram, the molecular vibration modes immediately after photoexcitation are only due to the reactant AVE. However, new bands appear at a delay of 2 ps. These new bands at 1750, 1030, and 1150 cm^{-1} are assigned to the C=O stretch ($\nu_{\mathrm{C=O}}$), the C–C–C symmetric stretch ($\nu_{\mathrm{s\,C\text{–}C\text{–}C}}$), and the C–C–C asymmetric stretch ($\nu_{\mathrm{as\,C\text{–}C\text{–}C}}$), respectively. The frequencies of these new modes correlate well with the frequencies of the Raman spectrum of synthesized allylacetaldehyde (Figure S3 in SI) by the oxidaton of 4-penten-1-ol. Therefore, the appearance of the new modes verifies that allylacetaldehyde was generated. Furthermore, the NMR spectrum of AVE after the pump–probe experiment also proves the generation of allylacetaldehyde (Figure S4 in SI). The quantum yield of the photoinduced process was estimated to be about 0.01. As described above, the time-resolved conformation changes during the Claisen rearrangement were observed via molecular vibration change.

The detailed mechanism of the reaction was thus clarified and can be described as follows. Disappearance of the $\nu_{\mathrm{s\,C\text{–}O\text{–}C}}$

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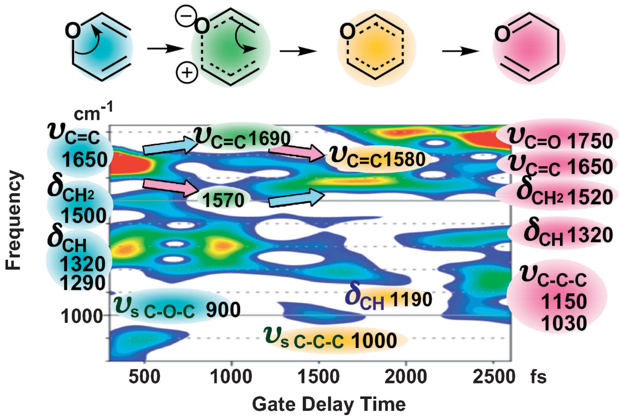

Figure 3. Spectrogram using a Blackman window function.

(890 cm^{-1}) and the δ_{CH_2} (1500 cm^{-1}) bands around 800 fs shows that the C^4–O bond is weakened or broken in the first step of the reaction. The frequency shift of the $\nu_{C=C}$ also suggests the weakening of the C^4–O bond as follows. The $\nu_{C=C}$ of the vinyl and allyl groups, observed at 1650 cm^{-1} just after photoexcitation, is separated in a blue-shifted mode toward 1690 cm^{-1} and a red-shifted mode toward 1570 cm^{-1} from 500 to 800 fs. These frequency shifts suggest that C^4–O bond weakening or breaking caused the electronic density in the vinyl and allyl groups to increase and decrease, respectively.

After the C^4–O bond weakening, electrons are transferred from the vinyl group to the allyl group to form a weak C^1–C^6 bond. This reduces the electronic density along the C^1=C^2 in the vinyl group resulting in the red shift of $\nu_{C=C}$. In the allyl group, the electronic density along the C^5=C^6 bond is increased to induce the blue shift of $\nu_{C=C}$, and the C^4–C^5 changes to a C^4=C^5. This makes the three C=C bonds (C^1=C^2, C^4=C^5, and C^5=C^6) equivalent and they have the same frequency of 1580 cm^{-1} at about 1500 fs delay. The frequency of 1580 cm^{-1} agrees fairly well with the frequency of $\nu_{C=C}$ in benzene known to be 1585 cm^{-1} from the literature.[13] Therefore, the appearance of a band around 1580 cm^{-1} implies that the generated intermediate has an aromatic-like six-membered structure including aromatic C=C bonds similar to those of benzene. The generation of aromatic-like six-membered structure is also supported from the appearance of $\delta_{C\text{–}H}$ and $\nu_{s\,C\text{–}C\text{–}C}$ at 1190 and 1000 cm^{-1}, respectively. Finally, C^4–O bond breaking and C^1–C^6 bond formation proceed simultaneously (i.e., in a synchronous concerted process) to generate the product.

The existence of a six-membered intermediate are suggested by the appearance of bands at 1000, 1190, and 1580 cm^{-1} at 1.5 ps followed immediately by a weak 1750 cm^{-1} band. This $\nu_{C=O}$ band intensity has highest value at about 2.2 ps when the five bands with frequencies 1030, 1150, 1320, 1520, and 1650 cm^{-1} appear. Therefore, the time constants of 2.2 ps does not necessarily reflect the formation time of the allylacetaldehyde but the time required for the accumulation of allylacetaldehyde to be detected by its vibration signals. Molecular vibration modes of 1000, 1190, and 1580 cm^{-1} were observed for about 500 fs or longer as seen in Figure 3. The reason why they could be observed for such a long period can be explained as follows. It is because the occurrence time to generate six-membered intermediate has variation depending on the thermal energy of the component molecules distributed over the Boltzmann distribution.

The present experimental results show that stimulated Raman excitation of vibrations drives the Claisen rearrangement in the ground state, and detailed reaction processes were clarified for AVE. It demonstrates that the observation of transition states by vibrational real-time spectroscopy opens a new methodology to study reactions in the ground state via the stimulated Raman excitation of coherent vibration using ultrashort visible laser pulse.

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References and Notes

1 L. Claisen, *Ber. Dtsch. Chem. Ges.* **1912**, *45*, 3157.

2 a) C. D. Hurd, M. A. Pollack, *J. Am. Chem. Soc.* **1938**, *60*, 1905. b) F. E. Ziegler, *Chem. Rev.* **1988**, *88*, 1423. c) U. Nubbemeyer, *Synthesis* **2003**, 961. d) A. M. M. Castro, *Chem. Rev.* **2004**, *104*, 2939. e) W. v. E. Doering, W. R. Roth, *Tetrahedron* **1962**, *18*, 67. f) P. Vittorelli, T. Winkler, H.-J. Hansen, H. Schmid, *Helv. Chim. Acta* **1968**, *51*, 1457. g) J. J. Gajewski, J. Jurayj, D. R. Kimbrough, M. E. Gande, B. Ganem, B. K. Carpenter, *J. Am. Chem. Soc.* **1987**, *109*, 1170. h) R. L. Vance, N. G. Rondan, K. N. Houk, F. Jensen, W. T. Borden, A. Komornicki, E. Wimmer, *J. Am. Chem. Soc.* **1988**, *110*, 2314. i) H. Hu, M. N. Kobrak, C. Xu, S. Hammes-Schiffer, *J. Phys. Chem. A* **2000**, *104*, 8058.

3 R. Hoffmann, R. B. Woodward, *Acc. Chem. Res.* **1968**, *1*, 17.

4 K. Fukui, *Acc. Chem. Res.* **1971**, *4*, 57.

5 a) O. Wiest, K. A. Black, K. N. Houk, *J. Am. Chem. Soc.* **1994**, *116*, 10336. b) J. G. Hill, P. B. Karadakov, D. L. Cooper, *Theor. Chem. Acc.* **2006**, *115*, 212. c) M. J. S. Dewar, E. F. Healy, *J. Am. Chem. Soc.* **1984**, *106*, 7127. d) M. J. S. Dewar, C. Jie, *J. Am. Chem. Soc.* **1989**, *111*, 511. e) J. J. Gajewski, N. D. Conrad, *J. Am. Chem. Soc.* **1979**, *101*, 2747. f) L. Kupczyk-Subotkowska, W. H. Saunders, Jr., H. J. Shine, W. Subotkowski, *J. Am. Chem. Soc.* **1994**, *116*, 7088. g) M. M. Davidson, I. H. Hillier, *J. Phys. Chem.* **1995**, *99*, 6748. h) J. J. Gajewski, *Acc. Chem. Res.* **1997**, *30*, 219. i) H. Y. Yoo, K. N. Houk, *J. Am. Chem. Soc.* **1997**, *119*, 2877. j) M. P. Meyer, A. J. DelMonte, D. A. Singleton, *J. Am. Chem. Soc.* **1999**, *121*, 10865.

6 Supporting Information is available electronically on the CSJ-Journal Web site, http://www.csj.jp/journals/chem-lett/index.html.

7 A. Baltuška, T. Fuji, T. Kobayashi, *Opt. Lett.* **2002**, *27*, 306.

8 In this work, many vibrational modes are excited via Raman excitation because of broad bandwidth of the pump pulse. The relaxation of those vibration modes proceeds in parallel with "reaction." Being different from T theoretical TS, the signal observed in this work shows vibration frequency changes caused by not only reaction itself but also molecular structural change etc. The molecular structure is thought to change gradually between the reactant, the TS, and the product. The state, which is continuously changing its structure between stable states (the reactant and the product), is called as "molecular structure change states including the TS."

9 AVE stored in a glass cell (volume: 400 mm^3) to be used as the solution sample at 295 ± 1 K. The experiments were performed at pump and probe intensities of 150 and 25 µW, respectively.

10 a) N. C. Blais, M. Zhao, D. G. Truhlar, D. W. Schwenke, D. J. Kouri, *Chem. Phys. Lett.* **1990**, *166*, 11. b) D. A. V. Kliner, D. E. Adelman, E. N. Zare, *J. Chem. Phys.* **1991**, *95*, 1648. c) K. Mikulecky, K.-H. Gericke, *J. Chem. Phys.* **1993**, *98*, 1244. d) F. F. Crim, *J. Phys. Chem.* **1996**, *100*, 12725.

11 a) I. Iwakura, A. Yabushita, T. Kobayashi, *J. Am. Chem. Soc.* **2009**, *131*, 688. b) A. T. N. Kumar, F. Rosca, A. Widom, P. M. Champion, *J. Chem. Phys.* **2001**, *114*, 6795.

12 M. J. J. Vrakking, D. M. Villeneuve, A. Stolow, *Phys. Rev. A* **1996**, *54*, R37.

13 G. Herzberg, *Infrared and Raman Spectra*, Van Nostrand Reinhold, New York, **1945**.

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