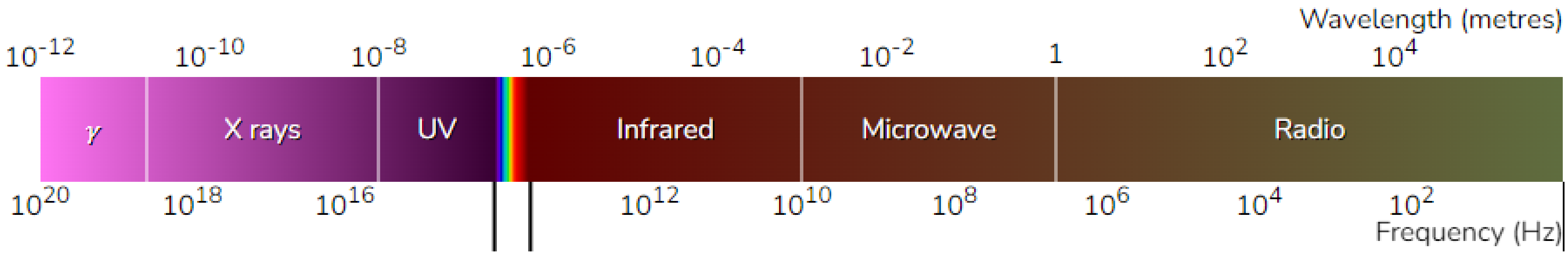
The Microwave Effects

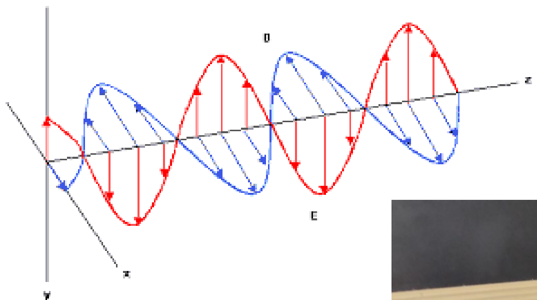
2023.5.6.
Shu Nakamura

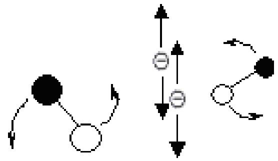
Contents

Microwave



Mainly, 2.45 GHz is used.





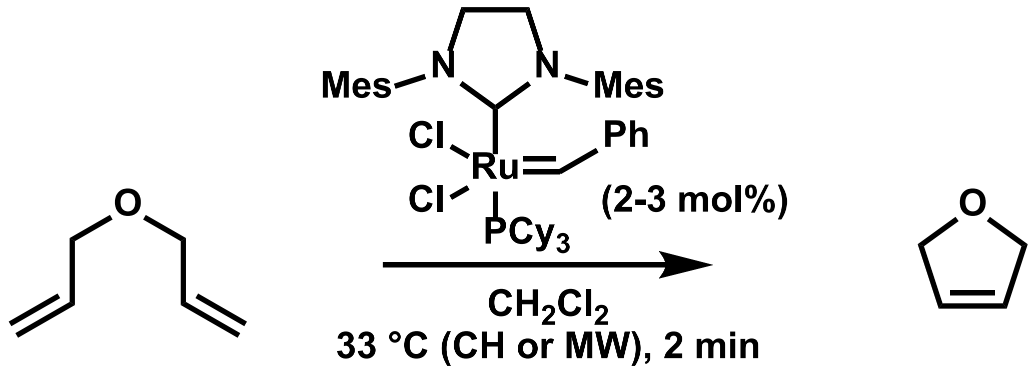
$$U = -\vec{\mu} \cdot \vec{E} = -\mu E \cos\theta$$

Simply…
→Dipole moment received energy from electromagnetic waves.

Microwaves heat molecules directly.
→rapid, volumetric, selective heating

1) https://www.acs.org/education/resources/undergraduate/chemistryincontext/interactives/radiation-from-sun/electromagnetic-spectrum.html
2) de la Hoz, A.; Díaz-Ortiz, Á.; Moreno, A. *Chem. Soc. Rev.* **2005**, *34*, 164.

Microwave Effects



Heating Method	Yield
CH (Conventional Heating)	4%
MW (Microwave Heating)	85%

Utilizing microwaves instead of an oil bath sometimes accelerate the reaction and improve the yield.

1) Mayo, K. G.; Nearhoof, E. H.; Kiddle, J. J. *Org. Lett.* **2002**, *4*, 1567.

Prof. de la Hoz and Naito

Prof. Antonio de la Hoz
1986 Ph.D @ Complutense University of Madrid
(Prof. José Elguero and Carmen Pardo)
1987 Postdoctral fellow @ Technical University of Denmark
(Prof. Mikael Begtrup)
1988 Assistant Professor @ the University of Castilla-La Mancha
2000-Professor @ the University of Castilla-La Mancha

Research topic: microwaves, flow methodologies, solvent-free reactions

Prof. Akira Naito

1978 Ph.D @ Kyoto University (Prof. Hiroyuki Hatano)
1978 Postdoctral fellow @ The University of British Columbia
(Prof. Charles Alexander McDowell)
1984 Assistant Professor @ Kyoto University
1990 Associate Professor @ Himeji Institute of Technology
2001 Professor @Yokohama National University
2015-Professor Emeritus @Yokohama National University

Research topic: solid NMR, structural biology

1) https://orcid.org/0000-0002-7101-6910
2) https://supramat.uib.es/msoc-uclm/
3) https://nrid.nii.ac.jp/ja/nrid/1000080172245/

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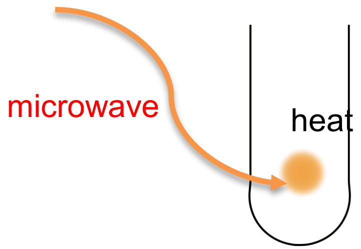
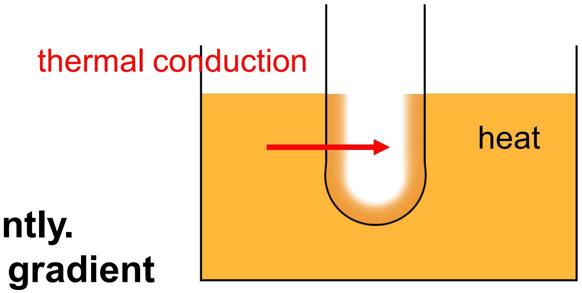
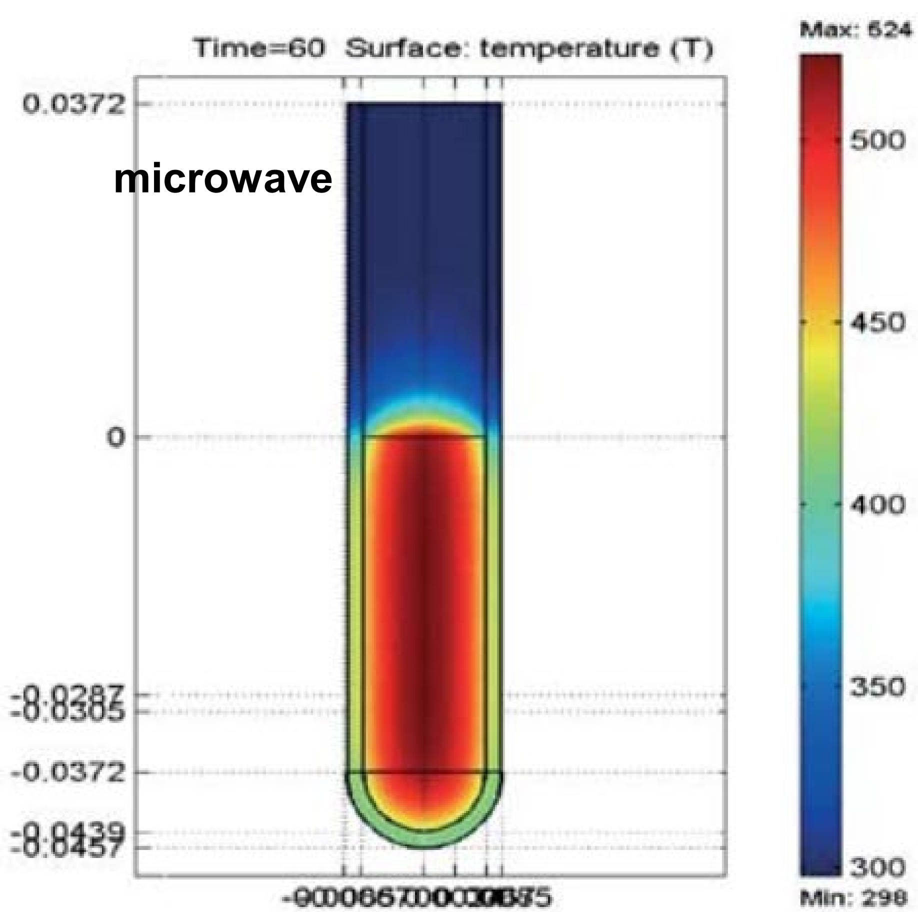
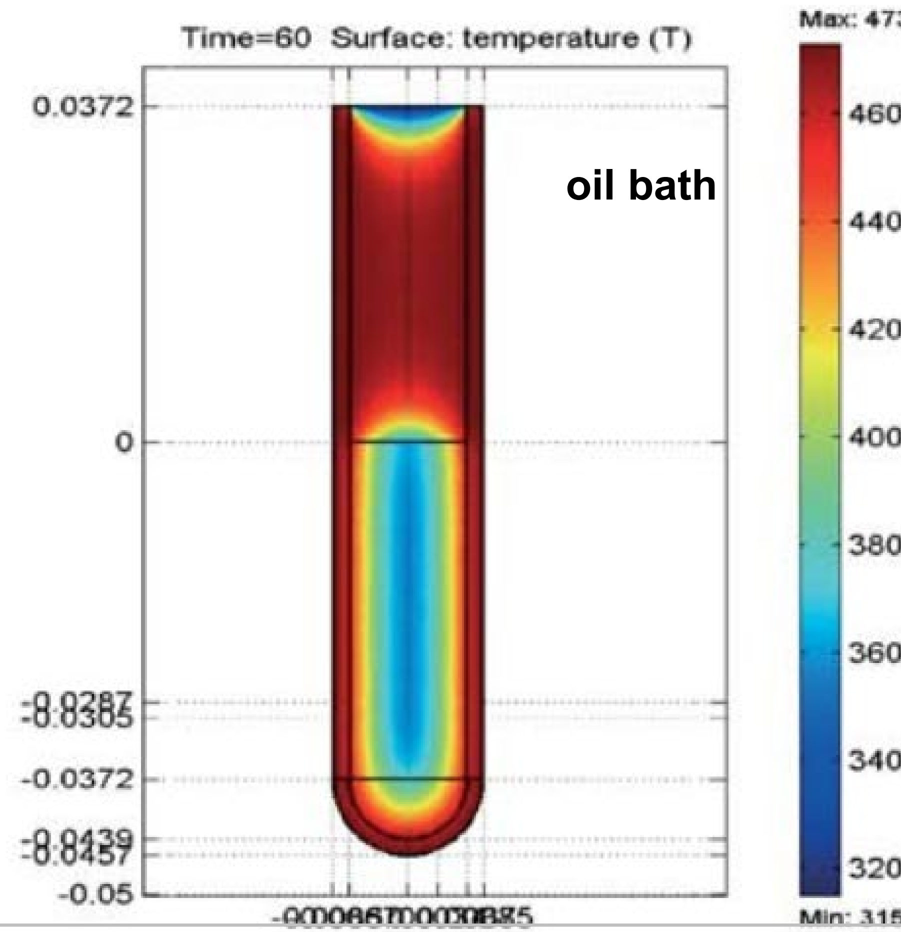
Thermal Effects (1) – Overheating





Microwaves heat differently.
→ inverted temperature gradient

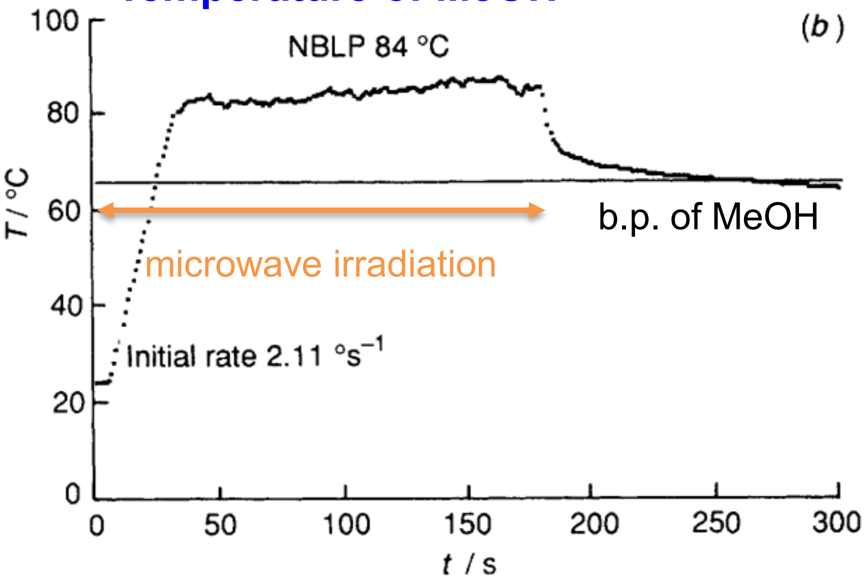




1) de la Hoz, A.; Díaz-Ortiz, Á.; Moreno, A. *Chem. Soc. Rev.* **2005**, *34*, 164.
2) Schanche, J. S. *Mol. Diversity* **2003**, *7*, 291.

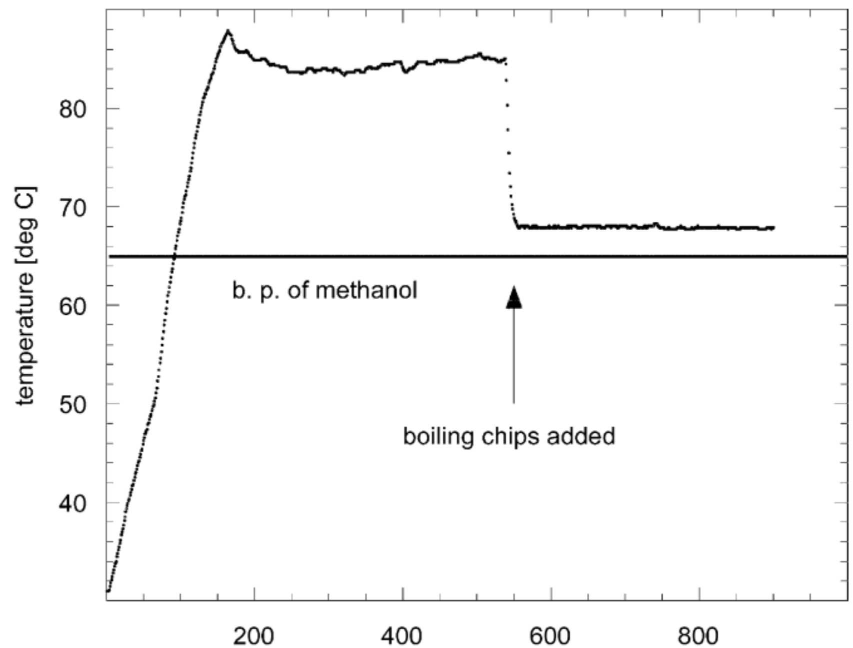
Thermal Effects (1) – Overheating

Temperature of MeOH



The boiling temperature of bulk liquid is higher than that of surface.
→The bulk liquid can be heated higher than b.p..

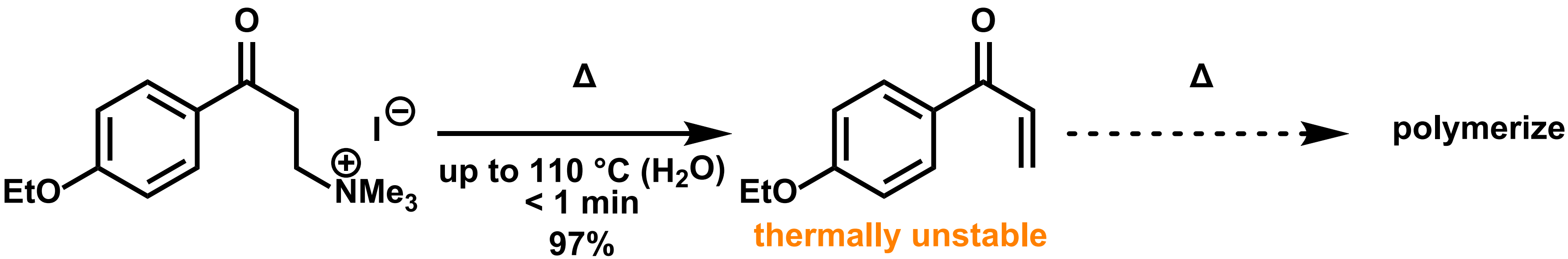
Overheating can be observed under reflux conditions.

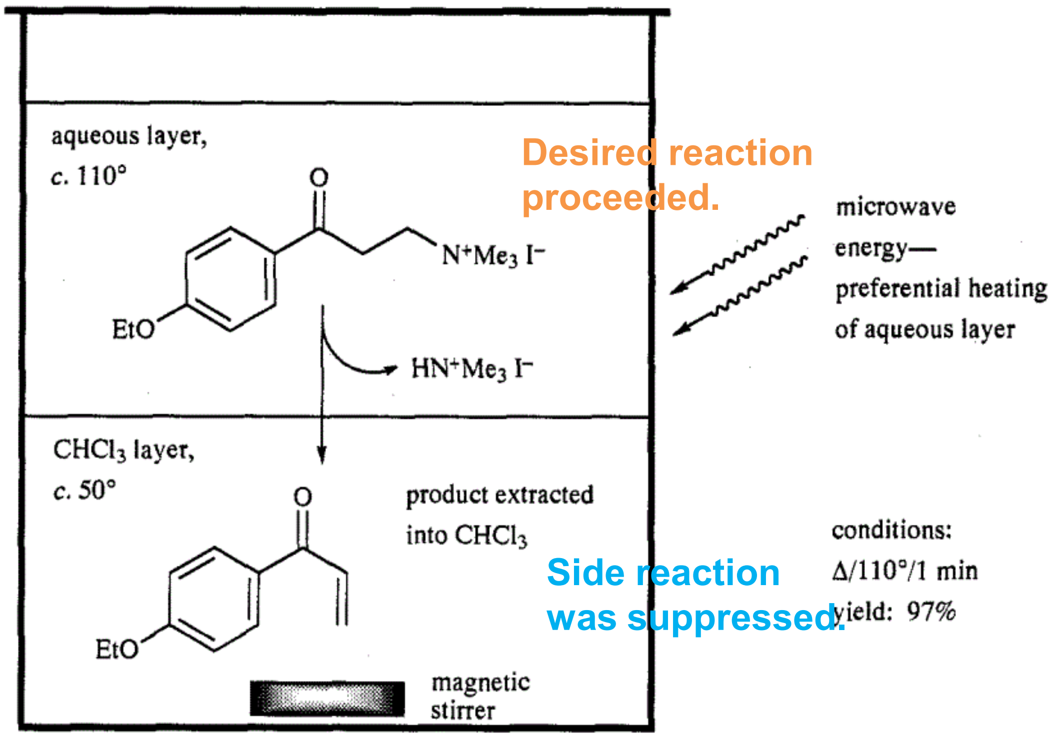


This effect can be achieved even in apolar solvents by adding polar molecules (ionic liquid, etc.).

1) Baghurst, D. R.; Mingos, D. M. P. *J. Chem. Soc., Chem. Commun.* **1992**, 674.
2) Klán, P.; Literák, J.; Relich, S. *J. Photochem. Photobiol., A* **2001**, *143*, 49.
3) de la Hoz, A.; Díaz-Ortiz, Á.; Moreno, A. *Chem. Soc. Rev.* **2005**, *34*, 164.

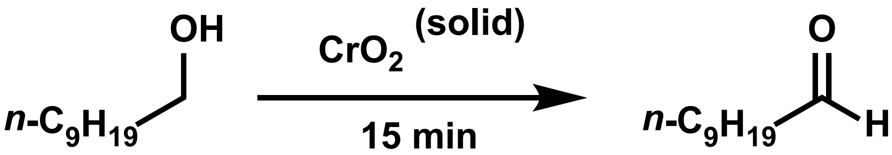
Thermal Effects (2) – Selective Heating





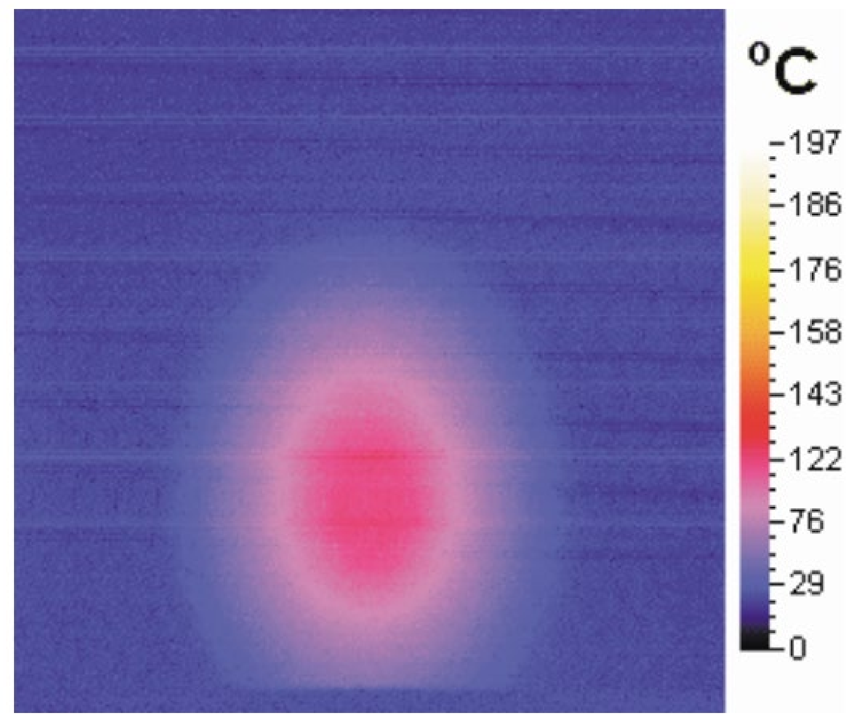
1) Raner, K. D.; Strauss, C. R.; Trainor, R. W. *J. Org. Chem.* **1995**, *60*, 2456.
2) Strauss, C. R.; Trainor, R. W. *Aust. J. Chem.* **1995**, *48*, 1665.
3) de la Hoz, A.; Díaz-Ortiz, Á.; Moreno, A. *Chem. Soc. Rev.* **2005**, *34*, 164.

Thermal Effects (2) – Selective Heating



MW: 85%
CH: 58%

Temperature of CrO_2 in toluene after MW irradiation for 2 min



Microwave selectively heated around the reagent.

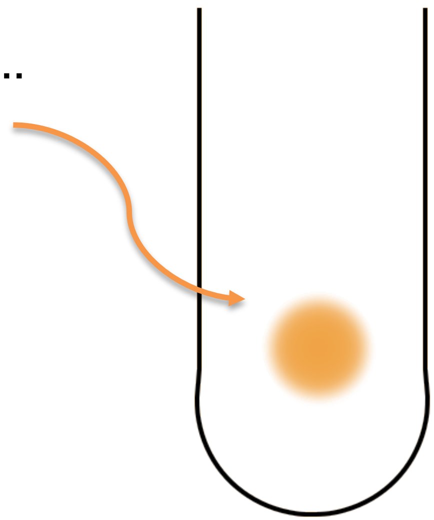
1) Bogdal, D.; Lukasiewicz, M.; Pielichowski, J.; Miciak, A.; Bednarz, Sz. *Tetrahedron* **2003**, *59*, 649.
2) de la Hoz, A.; Díaz-Ortiz, Á.; Moreno, A. *Chem. Soc. Rev.* **2005**, *34*, 164.

Thermal Effects

Microwave produce different thermal properties.

Microwave heating is…

- **rapid**
- **volumetric**
- **selective**



heterogenous temperature

- **accelerate reaction**
- **improve selectivity**

thermal effect

1) de la Hoz, A.; Díaz-Ortiz, Á.; Moreno, A. *Chem. Soc. Rev.* **2005**, *34*, 164.
2) Díaz-Ortiz, Á.; Prieto, P.; de la Hoz, A. *Chem. Rec.* **2019**, *19*, 85.

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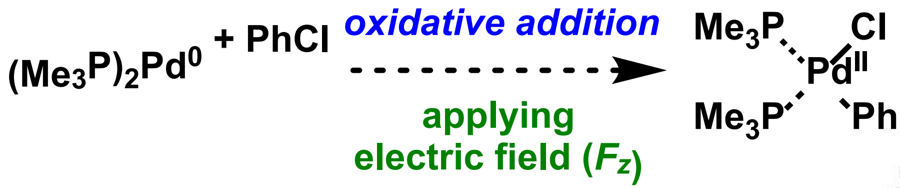
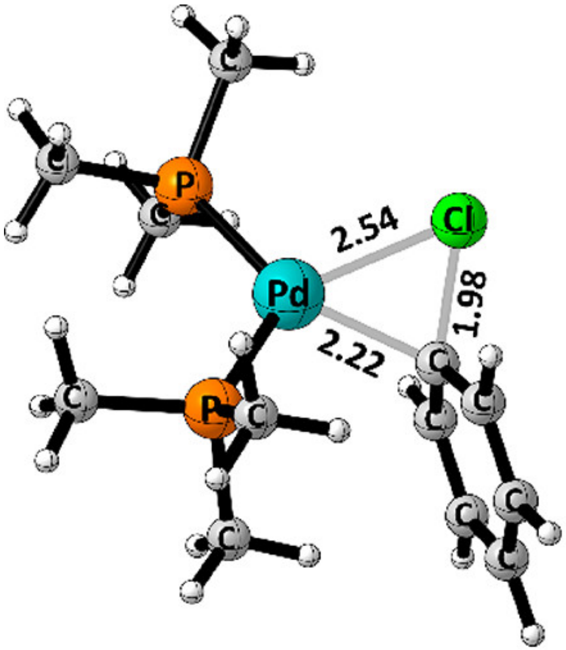
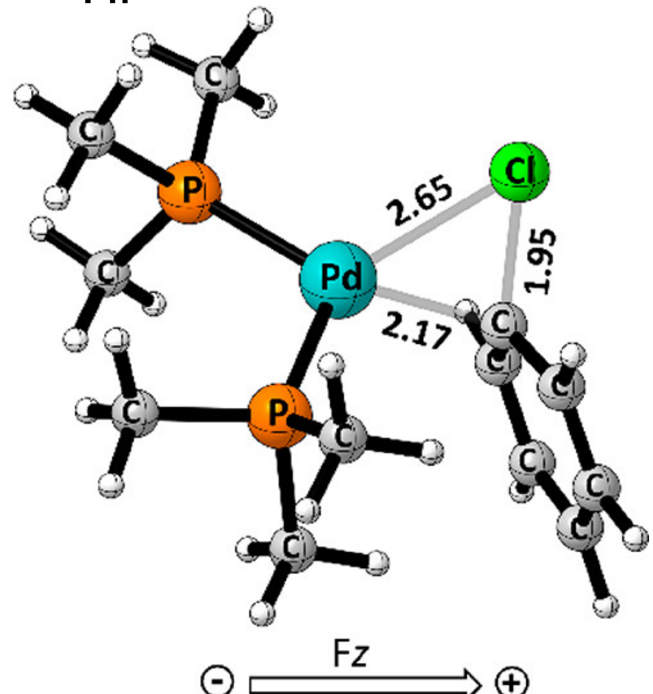
External Electric Field Effect





(a) Pristine Reaction
ΔE≠ = 13.2 kcal/mol



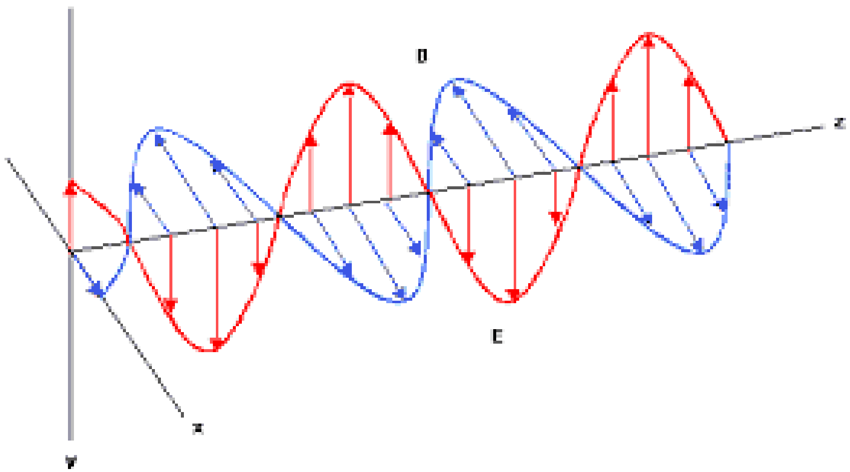
$\fallingdotseq 3.6 \times 10^9$ [V/m]

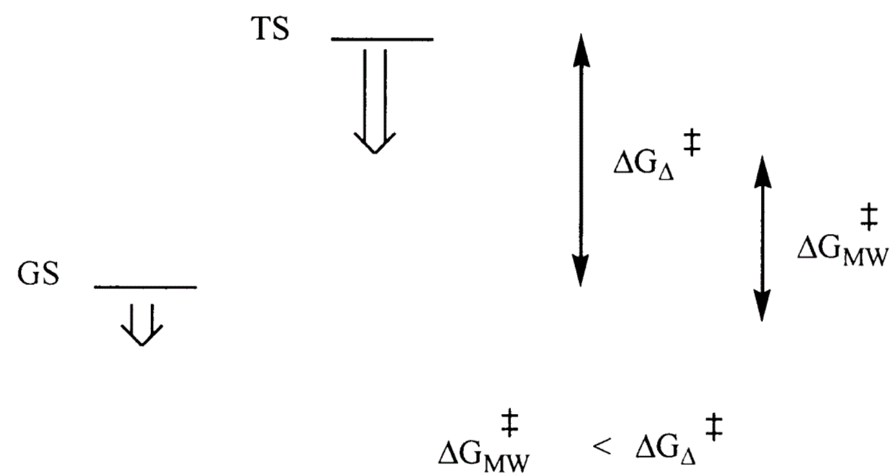
(c) Effect of Fz = +0.007 au Field
ΔE≠ = 4.4 kcal/mol

External electric field stabilizes the polarized transition state.
→enhance reaction

1) Joy, J.; Stuyver, T.; Shaik, S. *J. Am. Chem. Soc.* **2020**, *142*, 3836.

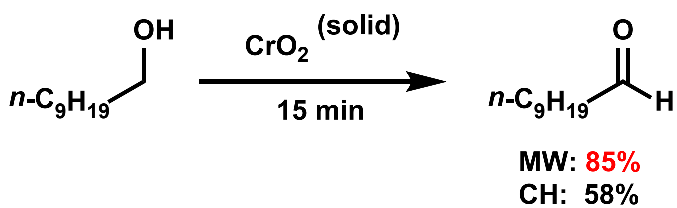
Nonthermal Effects

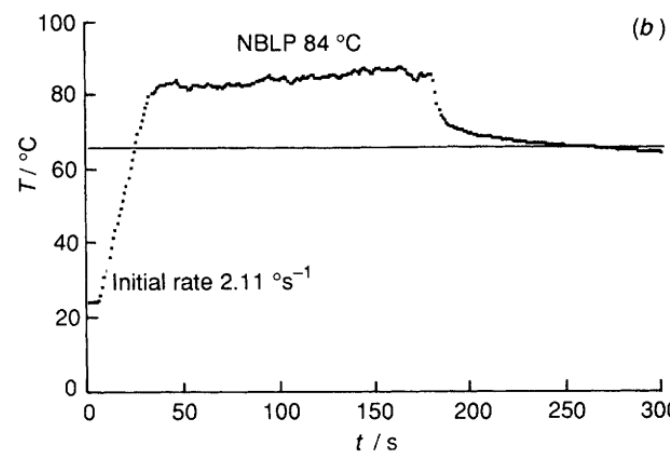




Microwaves have their electric and magnetic fields. → Microwaves would affect the activation energies?

However, microwaves produce different thermal properties.
→thermal effect

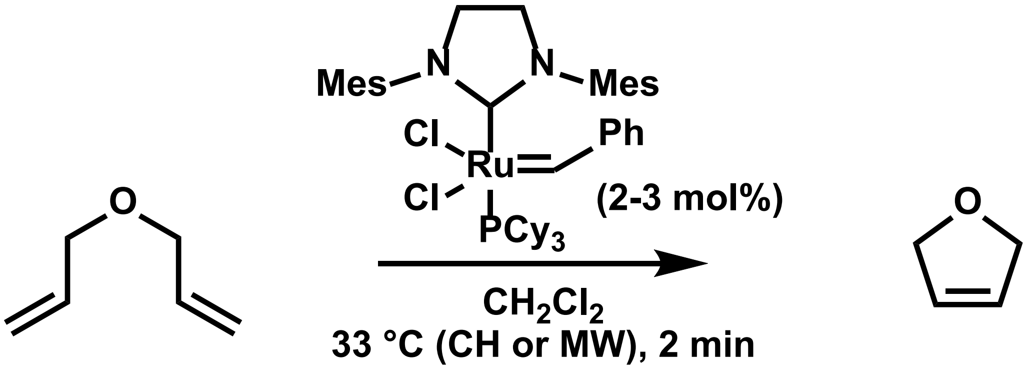




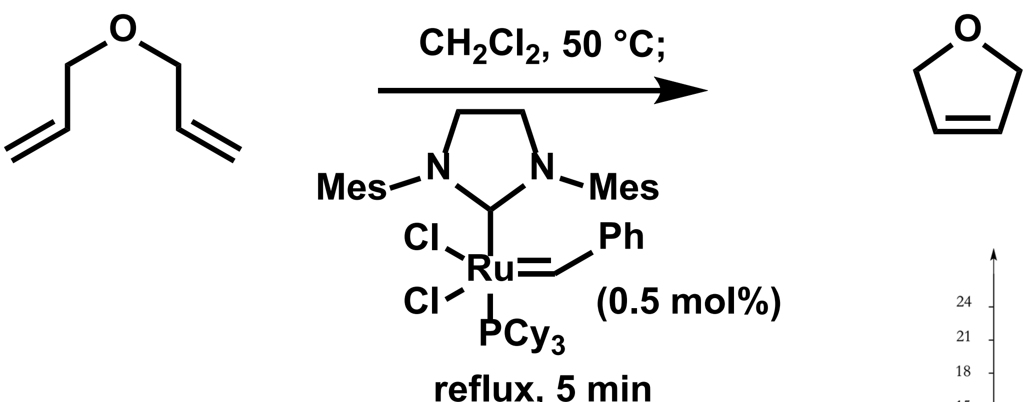
How do we distinguish nonthermal effects from thermal effects?

1) Perreux, L.; Louopy, A. *Tetrahedron* **2001**, *57*, 9199.
2) de la Hoz, A.; Díaz-Ortiz, Á.; Moreno, A. *Chem. Soc. Rev.* **2005**, *34*, 164.

Nonthermal? or Thermal?

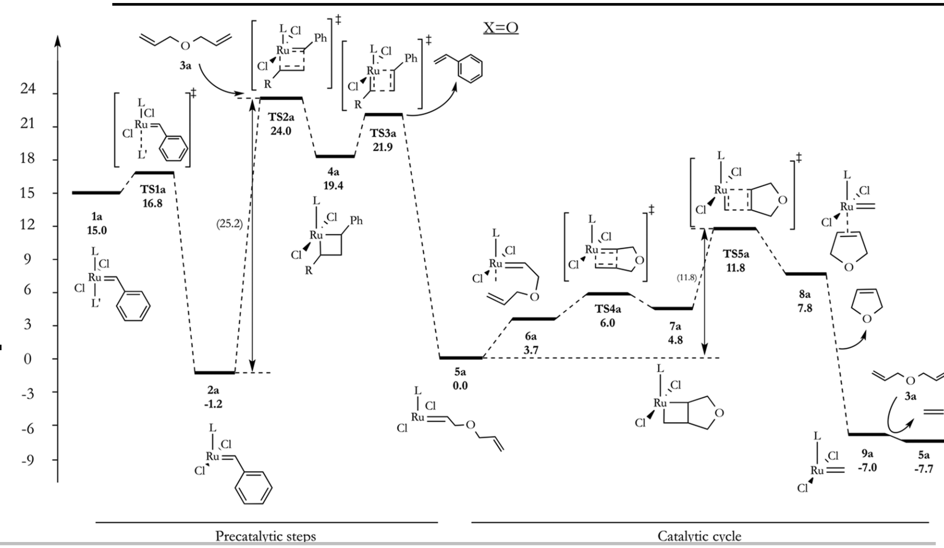


Heating Method	Yield
CH	4%
MW	85%



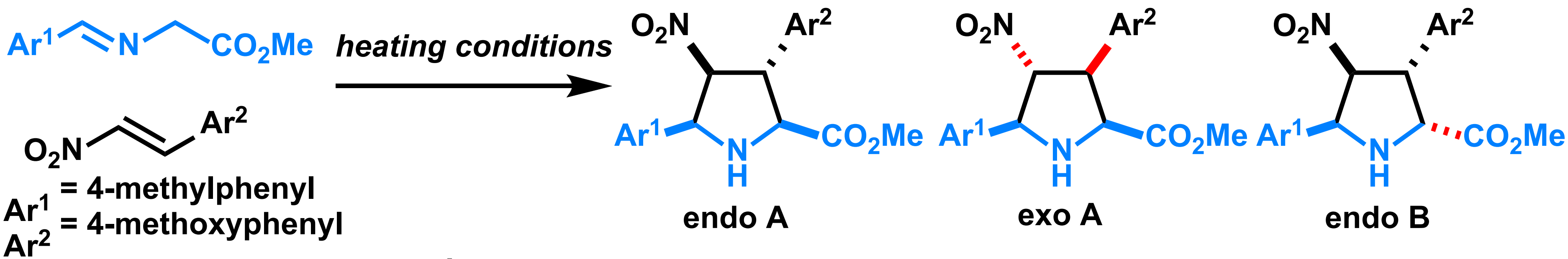
Heating Method	Yield
CH	65%
MW	70%

→**Only overheating accelerated the induction period.**



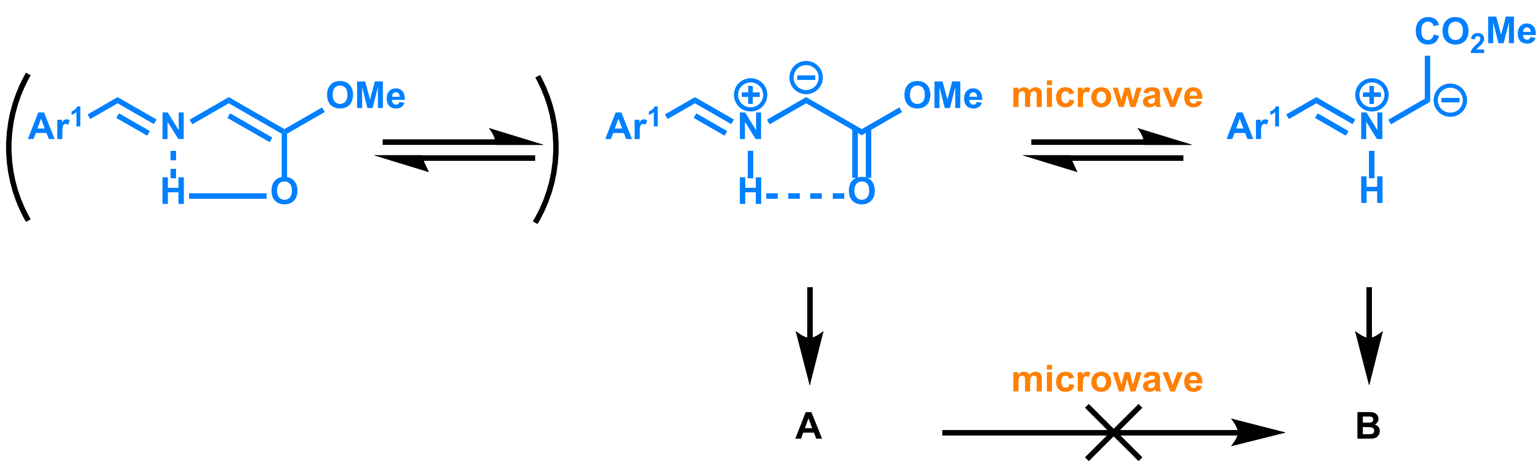
1) Garbacia, S.; Desai, B.; Lavastre, O.; Kappe, C. O. *J. Org. Chem.* **2003**, *68*, 9136.
2) Rodríguez, A. M.; Prieto, P.; de la Hoz, A.; Díaz-Ortiz, Á.; García, J. I. *Org. Biomol. Chem.* **2014**, *12*, 2436.

Nonthermal? or Thermal?



	endo A	exo A	endo B
toluene 112 °C (oil bath), 24 h	20%	23%	0%
neat 120 °C (MW), 10 min	28%	39%	20%

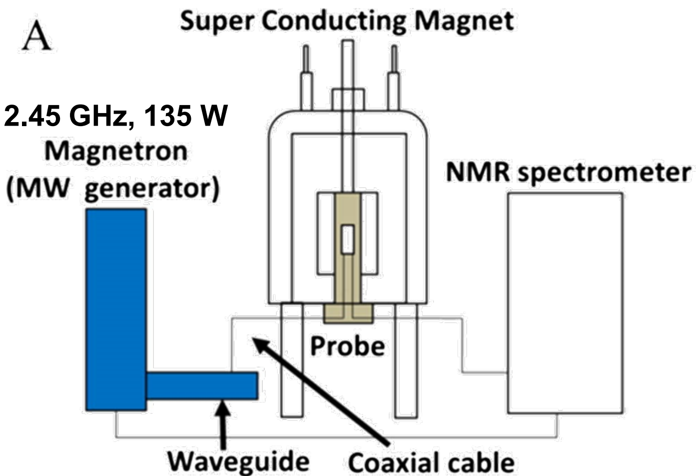
Active species (dipole) was changed?

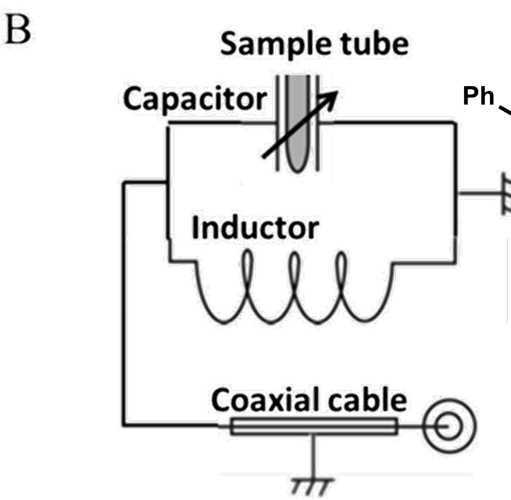


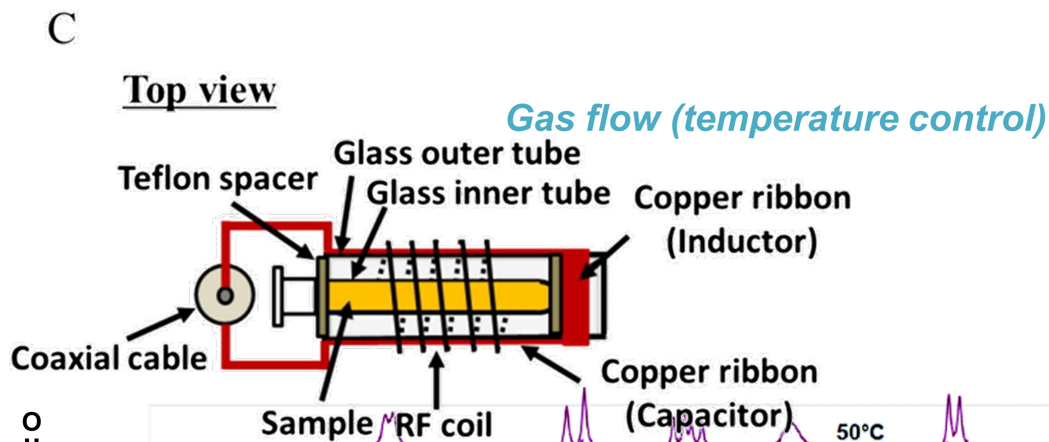
Nonthermal Effect?

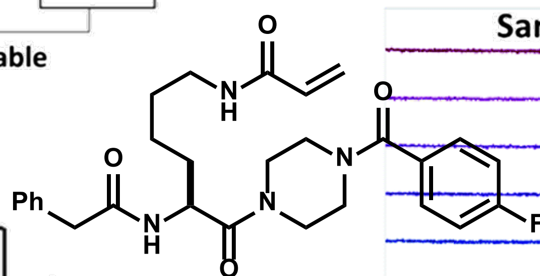
1) Díaz-Ortiz, Á.; de la Hoz, A.; Herrero, M. A.; Prieto, P.; Sánchez-Migallón, A.; Cossío, F. P.; Arrieta, A.; Vivanco, S.; Foces-Foces, C. *Mol. Diversity* **2003**, *7*, 175.
2) Vivanco, S.; Lecea, B.; Arrieta, A.; Prieto, P.; Morao, I.; Linden, A.; Cossio, F. P. *JACS* **2000**, *122*, 6078.

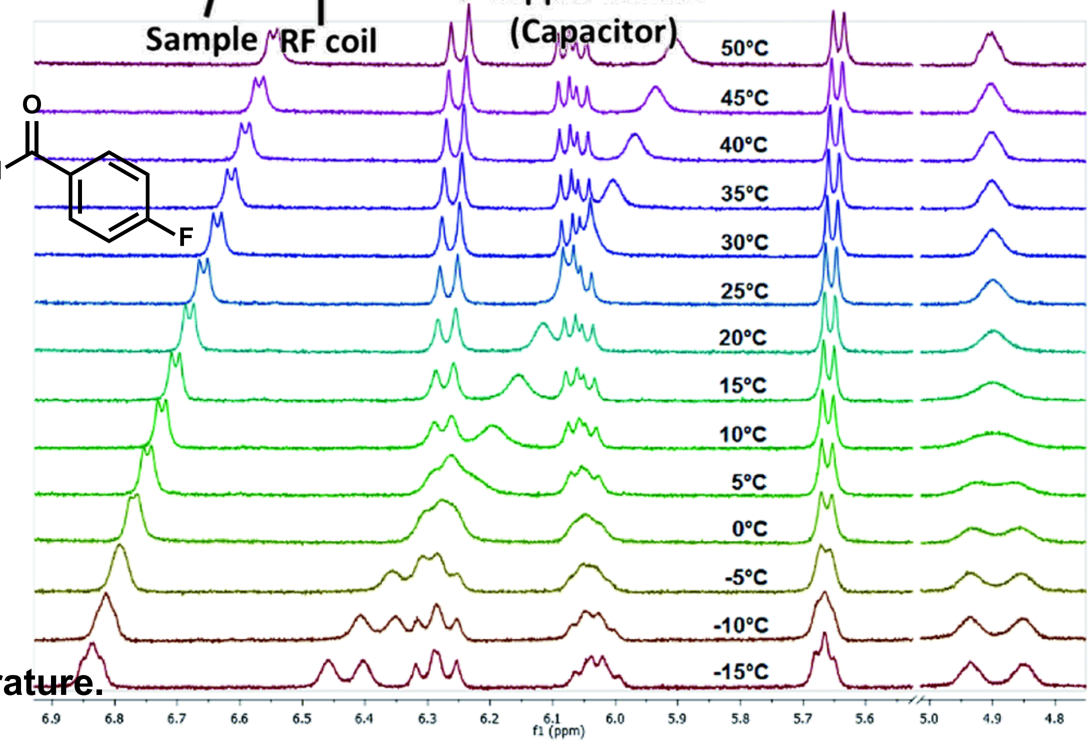
NMR Observation under Microwave Irradiation







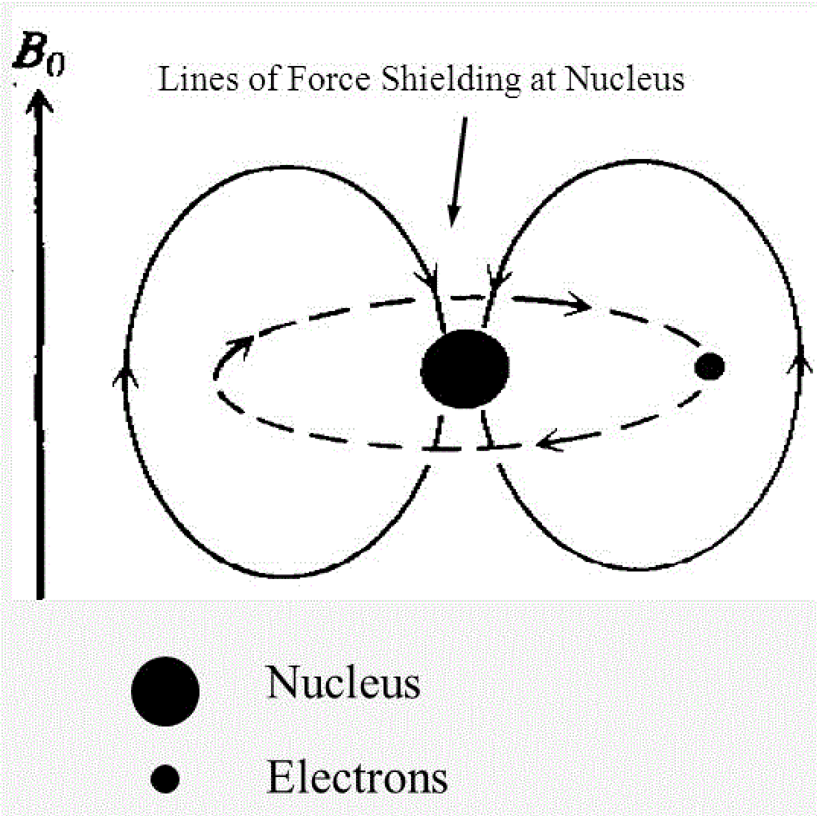


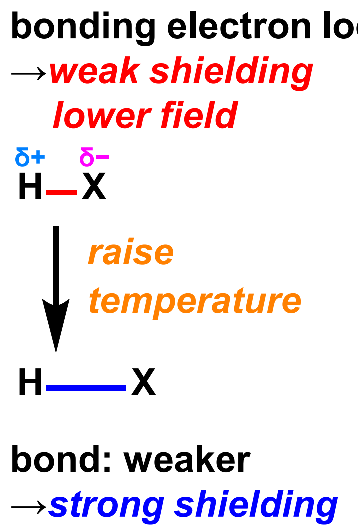


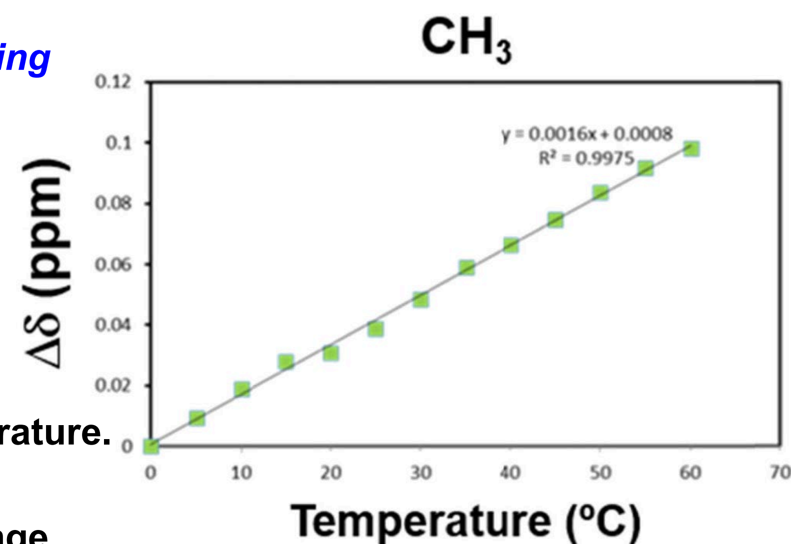
Chemical shifts are dependent on the temperature.
→***Temperature could be deduced?***

1) Tasei, Y.; Mijiddorj, B.; Fujito, T.; Kawamura, I.; Ueda, K; Naito, A. *J. Phys. Chem. B.* **2020**, *124*, 9615.
2) Tasei, Y.; Yamakami, T.; Kawamura, I.; Fujito, T.; Ushida, K.; Sato, M.; Naito, A. *J. Magn. Reson.* **2015**, *254*, 27.
3) Wodtke, R.; Steinberg, J.; Köckerling, M; Löser, R.; Mamat, C. *RSC Adv.* **2018**, *8*, 40921.

Chemical Shift Calibrated (CSC)-Temperature







A chemical shift usually goes to a higher field at raised temperature.

The correlation between δ and T is almost linear in a small range.
→Chemical shifts can be used as a thermometer of the bulk.

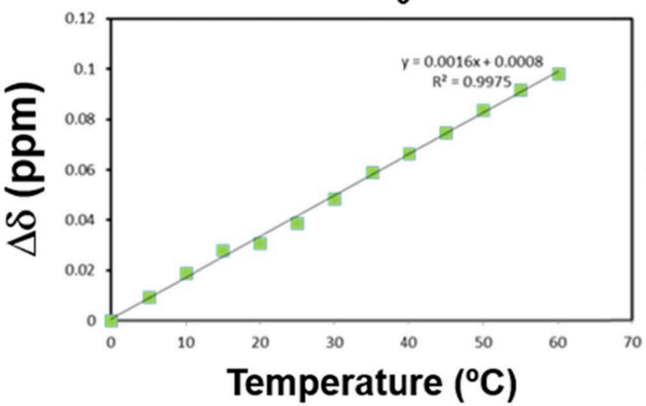
Observation of molecule and measurement of the temperature can be conducted at once under microwave irradiation.

1) Tasei, Y.; Mijiddorj, B.; Fujito, T.; Kawamura, I.; Ueda, K; Naito, A. *J. Phys. Chem. B.* **2020**, *124*, 9615.
2) https://slideplayer.com/slide/6374140/

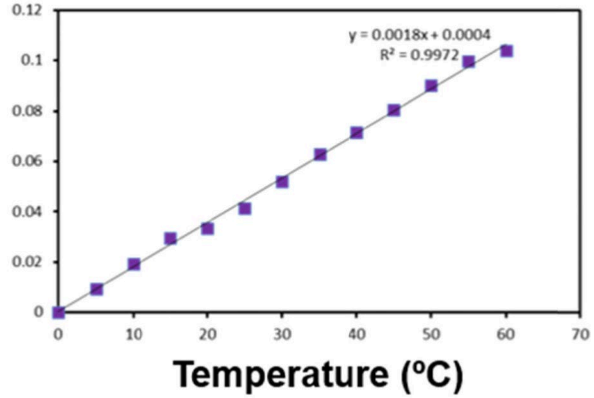
Temperature Calibration

Hexane

CH_3



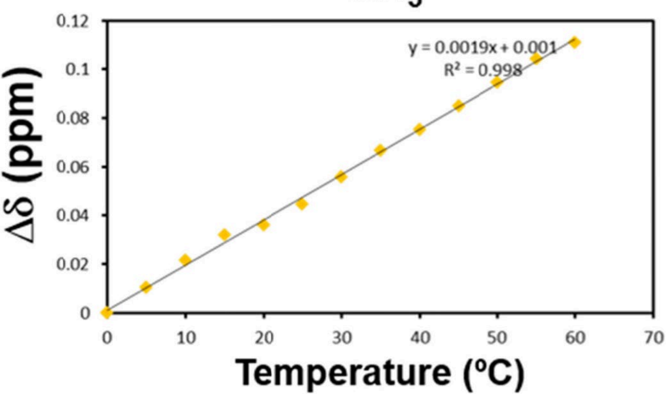
CH_2



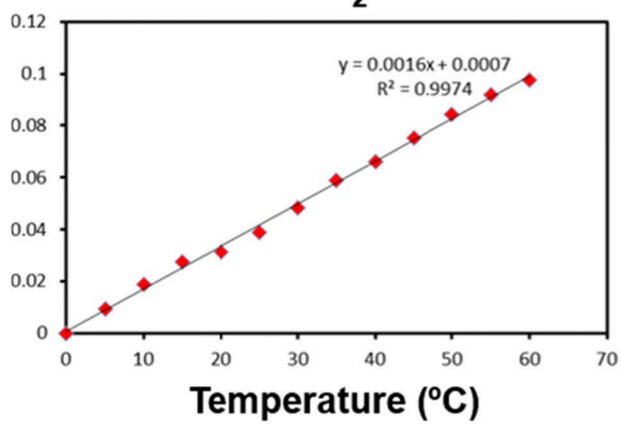
Temperatures were controlled by outer gas flow (for 30 min). (*conventional heating*)

Ethanol

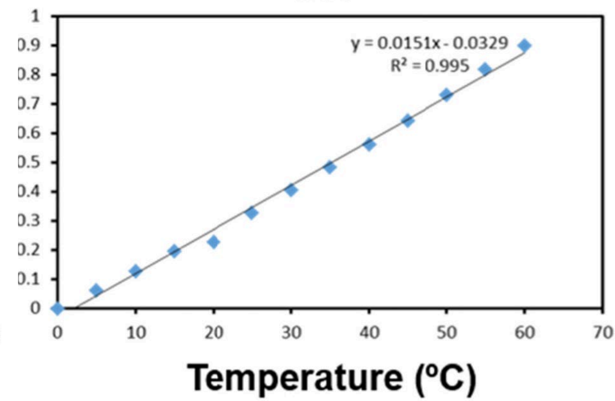
CH_3



CH_2



OH



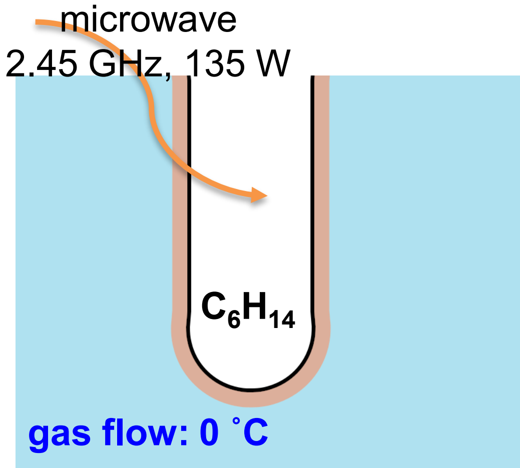
Linear correlations were obtained.

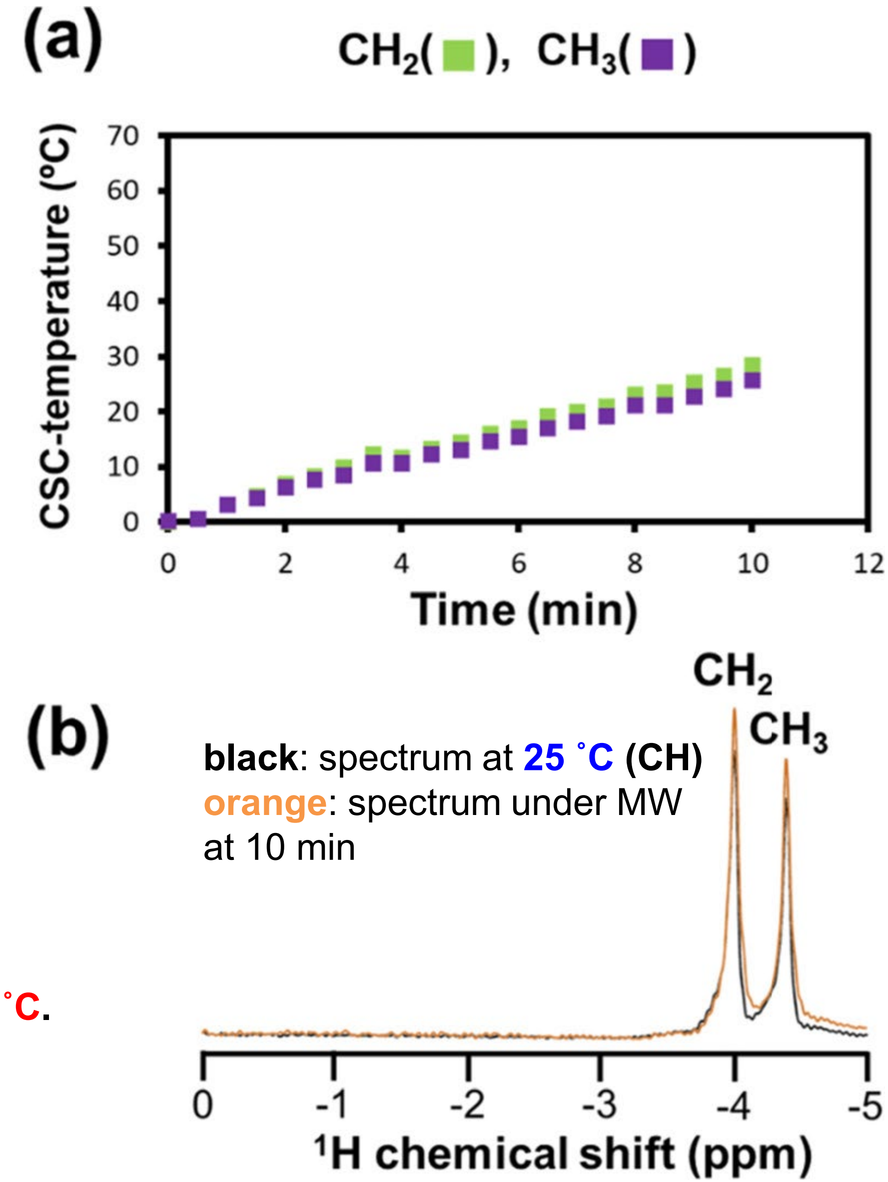
Large slope is thought to derive from the losing of hydrogen bonds.

1) Tasei, Y.; Mijiddorj, B.; Fujito, T.; Kawamura, I.; Ueda, K; Naito, A. *J. Phys. Chem. B.* **2020**, *124*, 9615.

2) Van Geet, A. L. *Anal. Chem.* **1968**, *40*, 2227.

Microwave Irradiation NMR (1) : Hexane

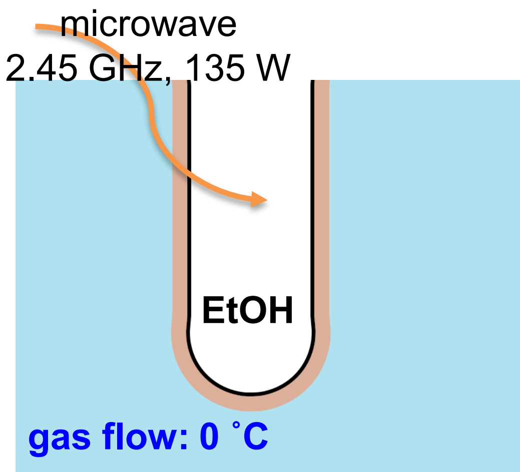


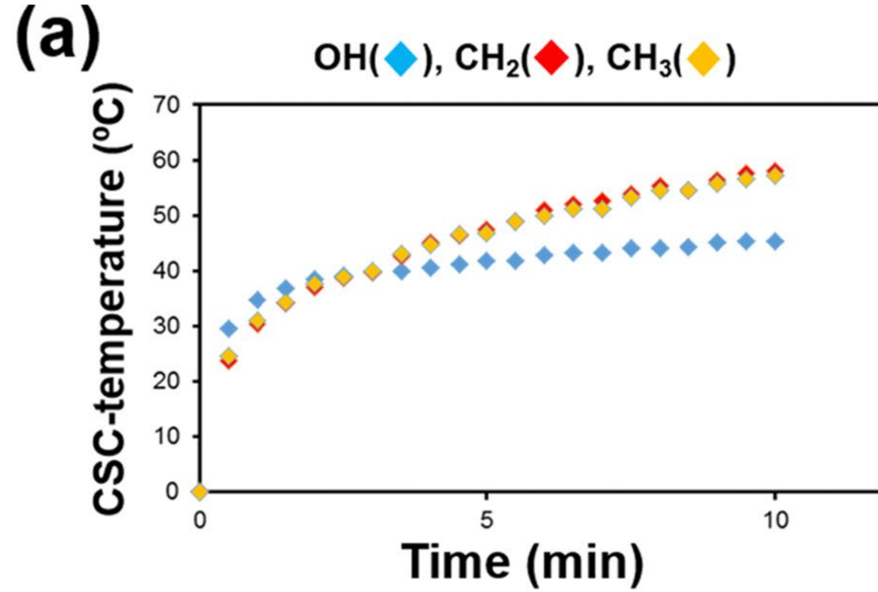


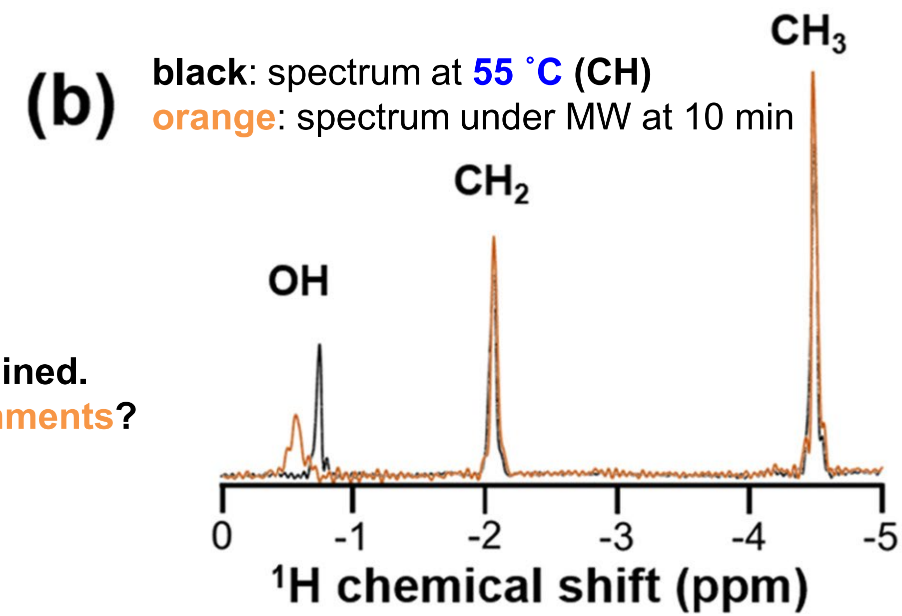
Same chart was obtained.
→The microwave only heated the hexane to 25 ˚C.

1) Tasei, Y.; Mijiddorj, B.; Fujito, T.; Kawamura, I.; Ueda, K; Naito, A. *J. Phys. Chem. B.* **2020**, *124*, 9615.

Microwave Irradiation NMR (2) : EtOH



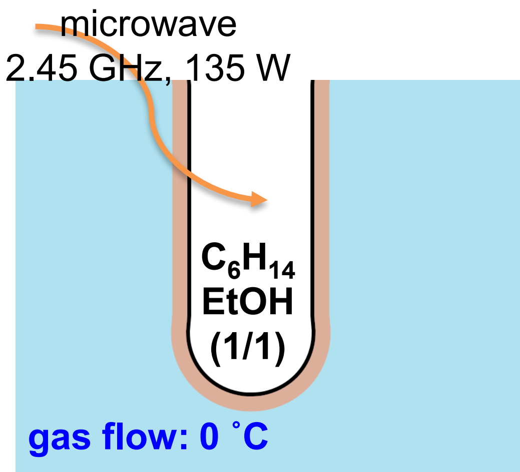




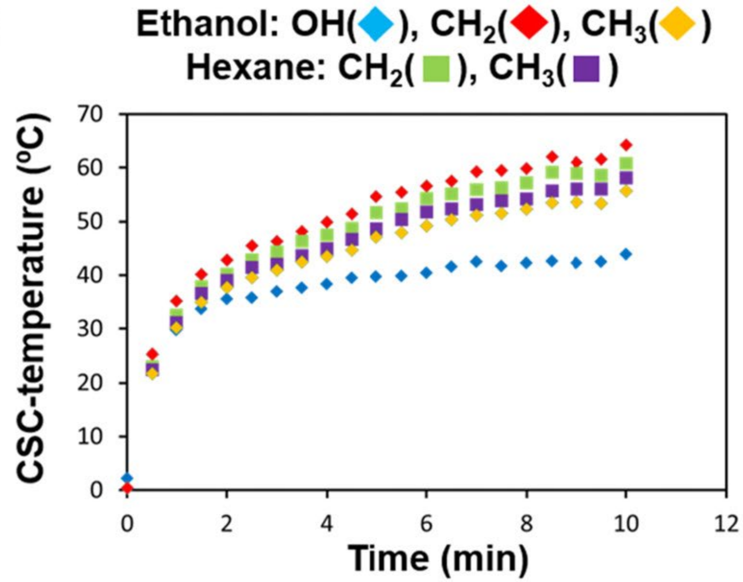
Different chart from conventional heating was obtained.
→The molecules of EtOH were set in different environments?

1) Tasei, Y.; Mijiddorj, B.; Fujito, T.; Kawamura, I.; Ueda, K; Naito, A. *J. Phys. Chem. B.* **2020**, *124*, 9615.

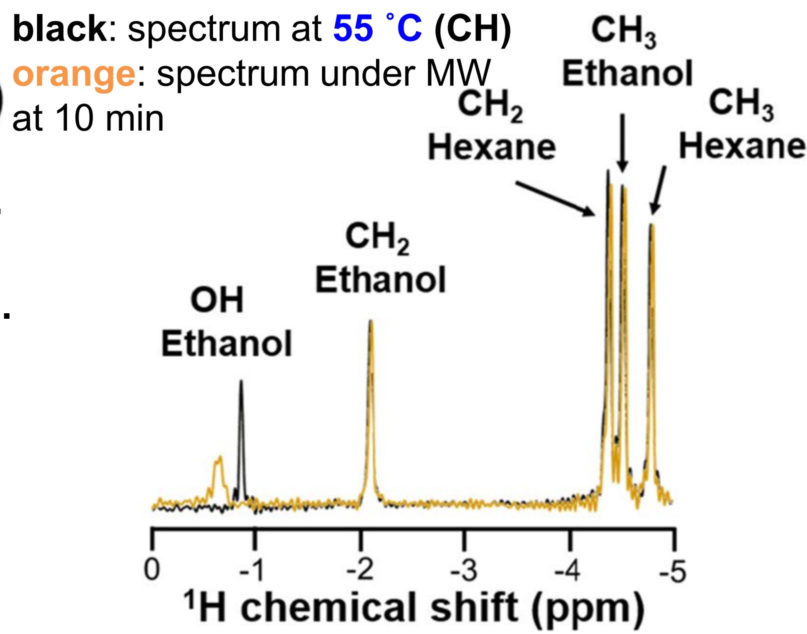
Microwave Irradiation NMR (3) : EtOH in Hexane



(a)



(b)



All aliphatic protons indicated the same temperature.
→CH_2 and CH_3 of EtOH really showed the bulk temperature.

Only OH shows strange chemical shift under MW irradiation.
→different hydrogen bonding…?

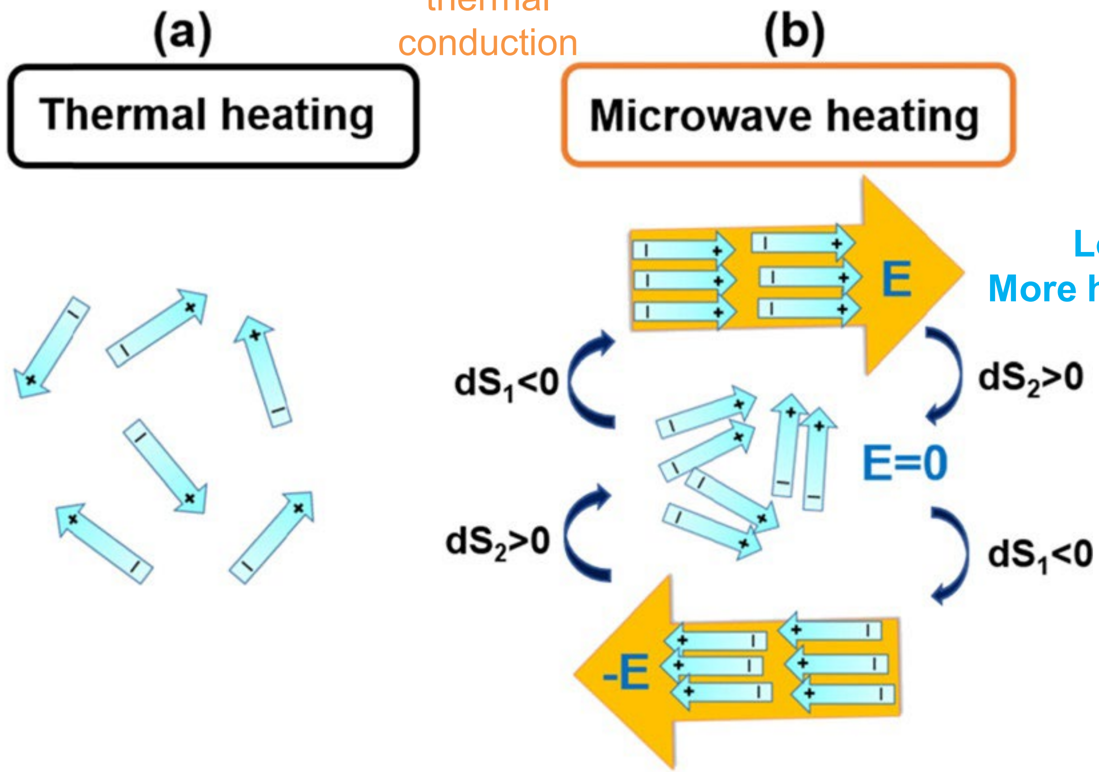
nonthermal effect

1) Tasei, Y.; Mijiddorj, B.; Fujito, T.; Kawamura, I.; Ueda, K; Naito, A. *J. Phys. Chem. B.* **2020**, *124*, 9615.
2) Van Geet, A. L. *Anal. Chem.* **1968**, *40*, 2227.

Proposed Nonthermal Effect

$$\Delta G = \underline{\Delta H} - T\Delta S$$

thermal conduction

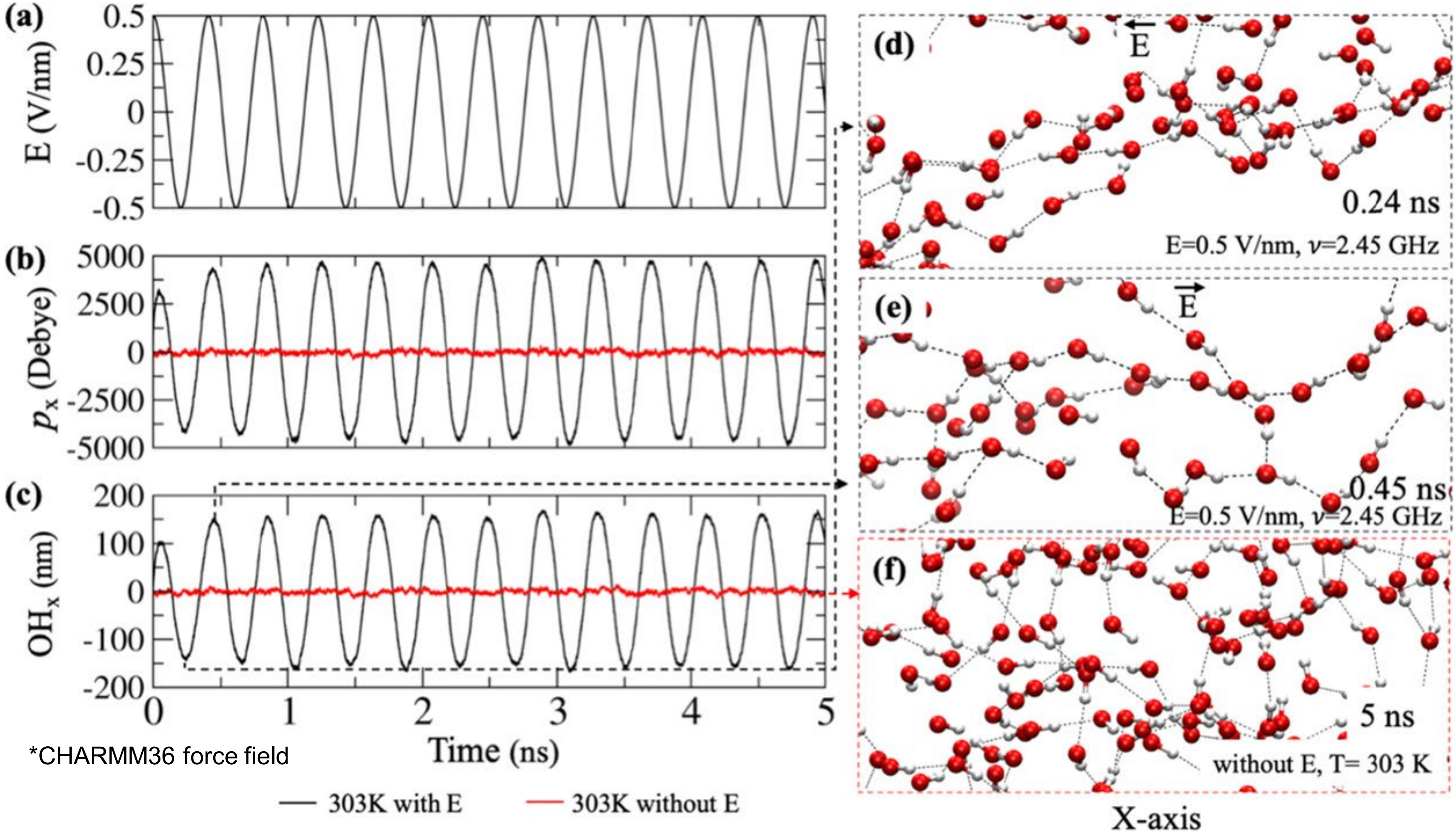


Low entropy
More hydrogen bonds

Microwaves (possible to transfer *W*) can affect entropy?

1) Tasei, Y.; Mijiddorj, B.; Fujito, T.; Kawamura, I.; Ueda, K; Naito, A. *J. Phys. Chem. B.* **2020**, *124*, 9615.

Molecular Dynamics Simulation



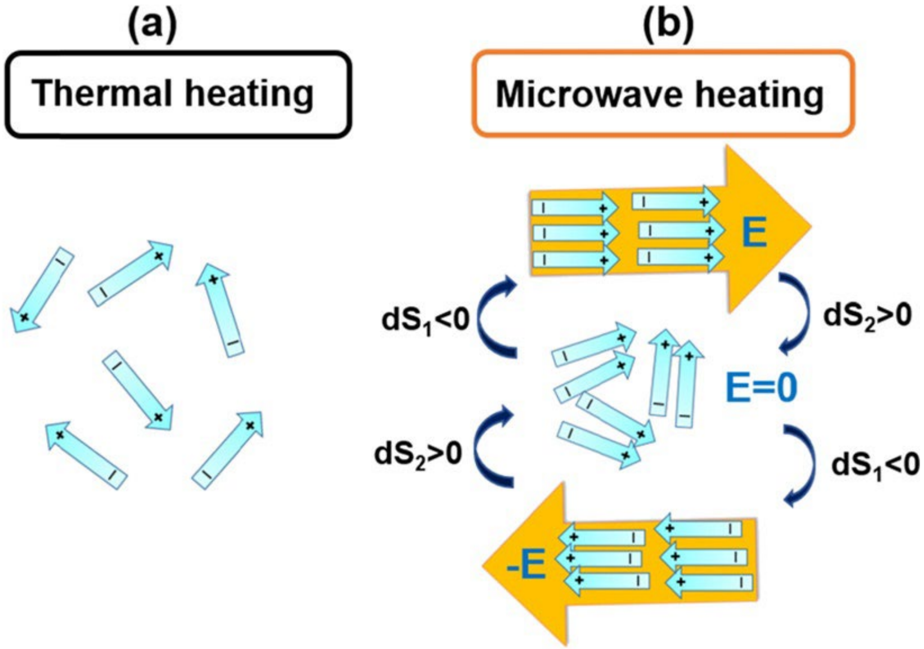
*CHARMM36 force field

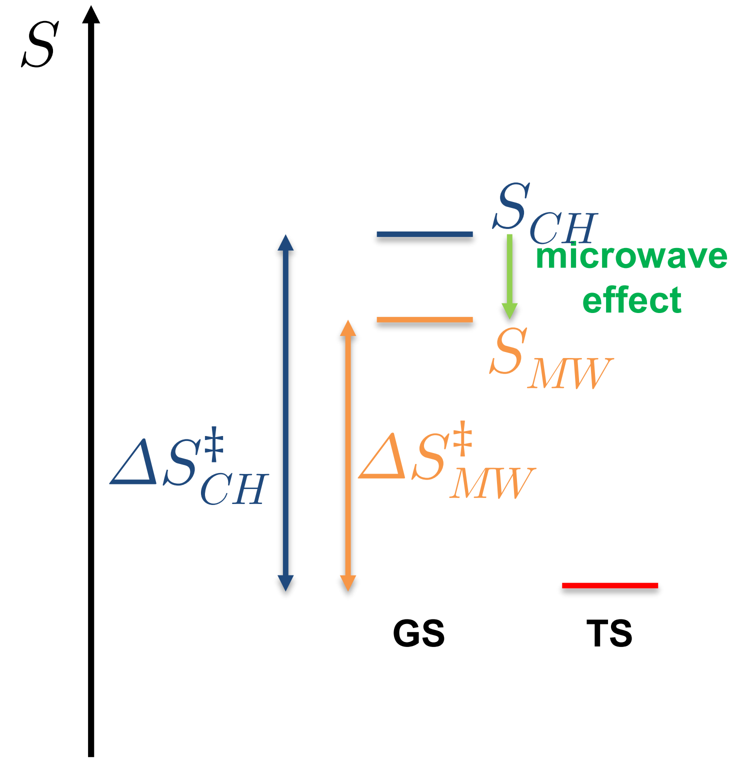
Polar molecules were oriented along the electric field (*E*).
(They also gathered to form hydrogen bonds.)

→Microwaves increase hydrogen bonds and reduce entropy.

1) Tasei, Y.; Mijiddorj, B.; Fujito, T.; Kawamura, I.; Ueda, K; Naito, A. *J. Phys. Chem. B.* **2020**, *124*, 9615.

Nonthermal Effect

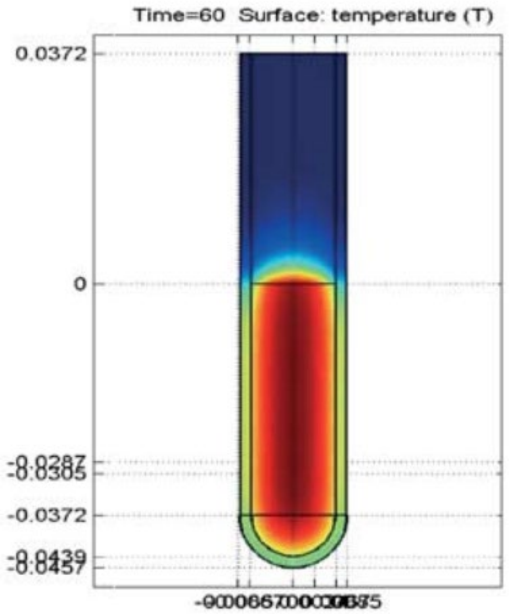




Microwaves can reduce the entropy of the ground state.

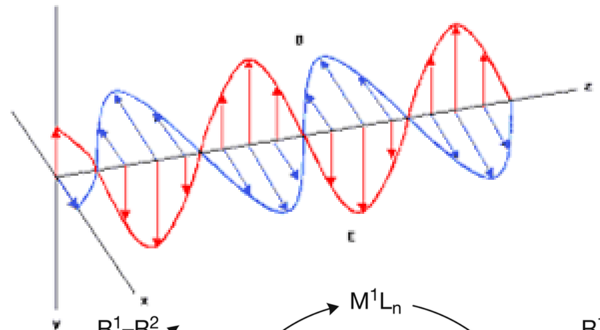
1) Tasei, Y.; Mijiddorj, B.; Fujito, T.; Kawamura, I.; Ueda, K; Naito, A. *J. Phys. Chem. B.* **2020**, *124*, 9615.

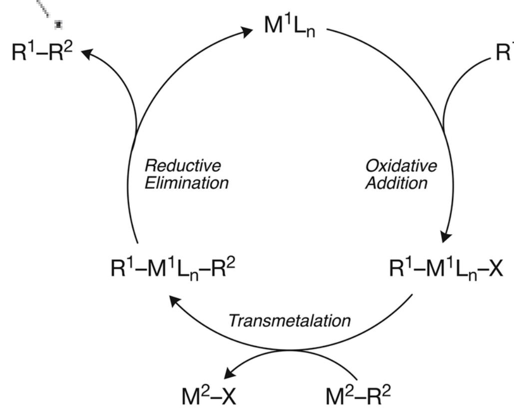
Summary

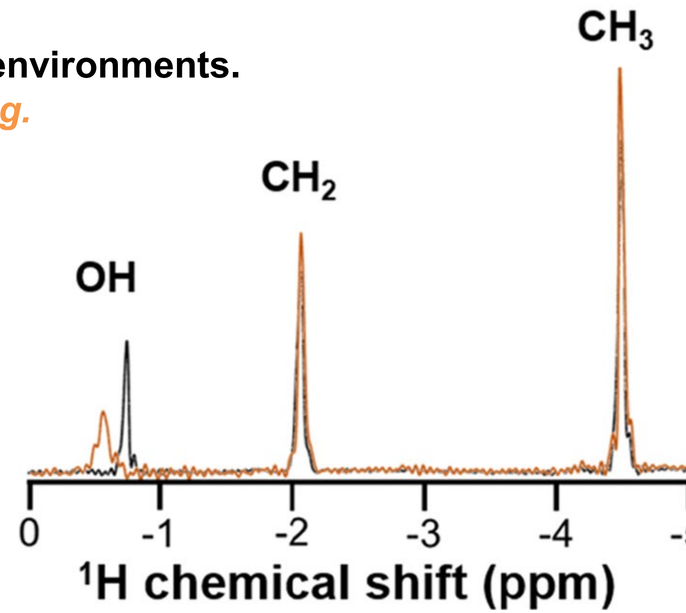


Microwaves produce different heating environments.

Not same as oil bath heating.







Thermal Effects

(heterogeneous heating)

- **Selective heating**
- **Overheating**

(raise *T* locally)

Nonthermal Effects

(applying electric field)

- **Stabilizing polarized transition state (reduce $\Delta H^\ddagger$)**
- **Orienting polar molecules (relief $\Delta S^\ddagger$)**

$$k(T) = \frac{k_B T}{h} e^{-\frac{\Delta H^\ddagger - T\Delta S^\ddagger}{RT}}$$

Microwaves can accelerate the reaction and improve the yield in some cases.

Microwave Effect

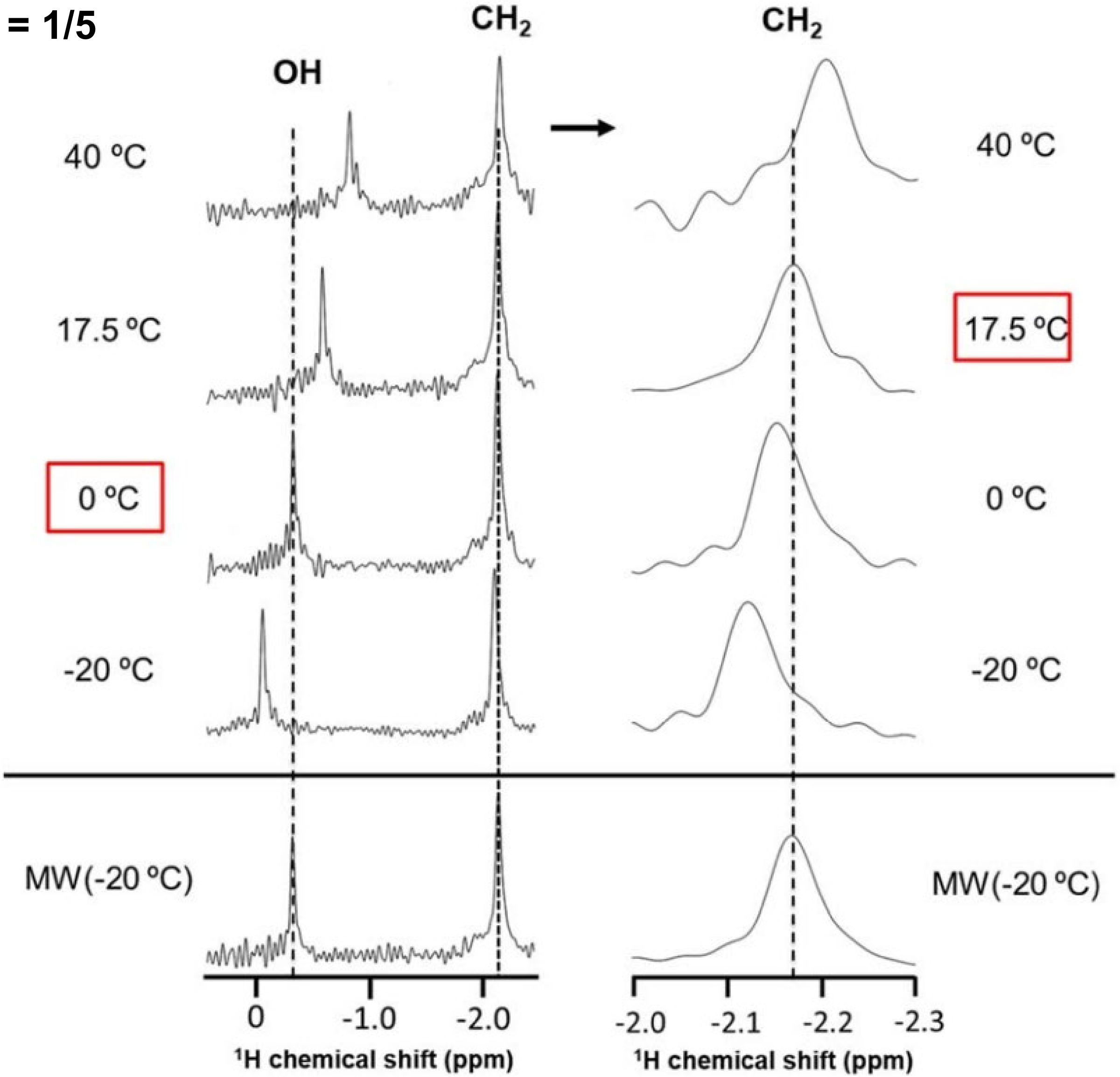
1) de la Hoz, A.; Díaz-Ortiz, Á.; Moreno, A. *Chem. Soc. Rev.* **2005**, *34*, 164.

2) Tasei, Y.; Mijiddorj, B.; Fujito, T.; Kawamura, I.; Ueda, K; Naito, A. *J. Phys. Chem. B.* **2020**, *124*, 9615.

Appendix

Comparing to -20 ˚C

EtOH/hexane = 1/5



1) Tasei, Y.; Mijiddorj, B.; Fujito, T.; Kawamura, I.; Ueda, K; Naito, A. *J. Phys. Chem. B.* **2020**, *124*, 9615.