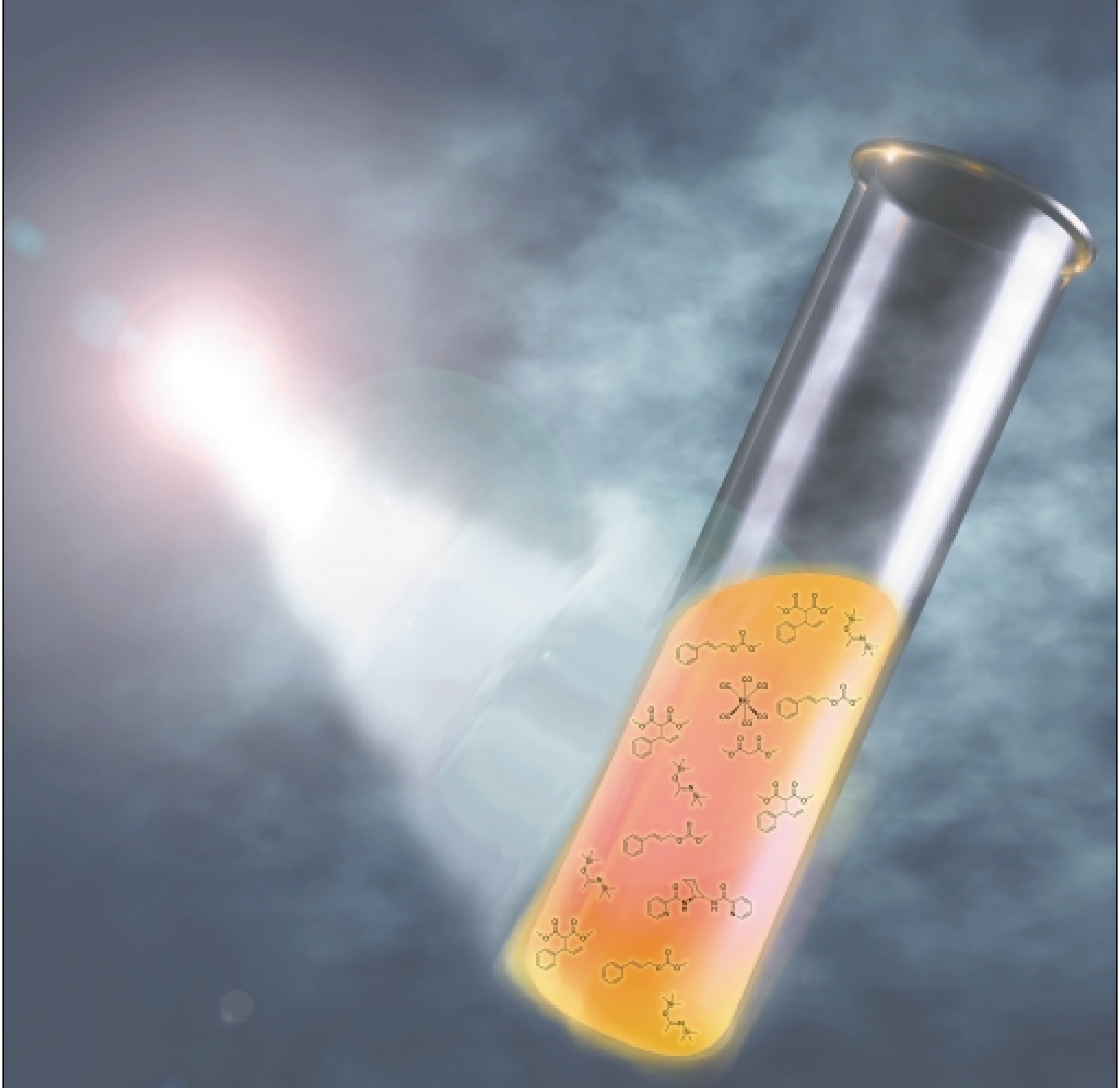
High-speed molybdenum-catalyzed asymmetric substitution can be performed with single-mode microwave heating. The reaction mixture is positioned inside the cavity and the microwave irradiation is released from the magnetron and strikes the sample from the top left.



Contrary to conventional conductive heating, microwave heat is generated inside the reaction mixture (in situ heating; no wall effects) and thus the sample is heated up evenly and very rapidly. This allows very selective organic reactions to be carried out in a highly reproducible fashion. More details are given on the following pages.

Fast, Convenient, and Efficient Molybdenum-Catalyzed Asymmetric Allylic Alkylation under Noninert Conditions: An Example of Microwave-Promoted Fast Chemistry**

Nils-Fredrik K. Kaiser, Ulf Bremberg, Mats Larhed,*
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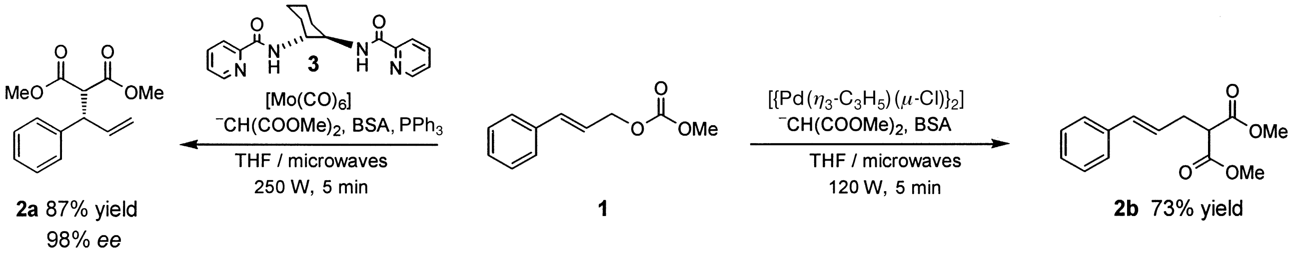
The delivery and distribution of energy has not yet attracted the attention it deserves among organic chemists. Modern focused microwave reactors are effective and reliable tools that could eliminate this neglect and become standard heating devices in chemical laboratories. Improved control of heating reactions opens new ways to achieve fast and selective synthesis, which is especially important in combinatorial processing.[1]

While investigating the scope and limitations of the new focused microwave technique,[2] we identified molybdenum(0)-catalyzed allylic malonate alkylation, innovatively developed by B. M. Trost et al., as a reaction suitable for study.[3] The reported two-step alkylation of methyl (*E*)-3-phenyl-2-propenyl carbonate (**1**) allows isolation of the product with high regio- and stereopurity but requires an inert atmosphere, reaction times of 2–3 h, and 10 mol% of the molybdenum(0) catalyst.[3c] Therefore, this reaction is a good subject for investigating the impact of microwave flash heating on product selectivity, shortening of reaction time, experimental convenience, and catalyst efficiency.

Previously, the molybdenum-catalyzed reactions were conducted with a preformed unstable [$(EtCN)_3Mo(CO)_3$] precatalyst.[3] We found it feasible to generate the catalyst system in situ from commercially available, stable [$Mo(CO)_6$] and ligand **3**. The allylic alkylations were conducted with microwave flash heating under air in a one-pot mixture of 0.04 equivalents of [$Mo(CO)_6$], 0.05 equivalents of **3**, allylic carbonate **1**, a freshly prepared solution of dimethyl sodiomalonate/dimethyl malonate (1/11), and *N,O*-bis(trimethylsilyl)acetamide (BSA).[4] Good reproducibility, complete conversion, high yields, and excellent *ee* values were achieved in only a few minutes (Scheme 1 and Table 1). In the standard solvent THF[3], an irradiation power of 250 W was sufficient for obtaining a reaction time of 5 min, 87% yield, and high regioselectivity and enantiomeric excess (98%) of **2a** (Table 1, entry 4). Somewhat lower regioselectivities (**2a**:**2b** = 17–19:1) were obtained in the one-pot microwave reactions (entries 1–5) than in the previously reported two-step method (**2a**:**2b** = 32–49:1).[3c] Using DME (entry 6) or 1,4-dioxane (entry 7) as solvent furnished higher yields and regioselectivities but lower reaction rates. Remarkably, the use of a nitrogen atmosphere did not improve the outcome of the reaction, while an oxygen atmosphere led to diminished catalyst activity (20% yield). Addition of small amounts of water (50 equivalents relative to catalyst) fully inhibited the catalysis. Triphenyl phosphite exhibited a similar but much weaker effect.[5] All attempts to use acetate as leaving group, instead of carbonate, were unsuccessful. Efforts to increase the turnover number by using 0.006 equivalents of [$Mo(CO)_6$] also failed.

The low solubility of dimethyl sodiomalonate in THF prompted us to search for ways to generate the anionic nucleophile in situ, for example, by decomposition of the leaving methyl carbonate anion.[6] Disappointingly, only very low yields of **2a** were obtained even at high temperatures. The use of BSA (probase) in conjunction with small amounts of anionic dimethyl malonate (9 mol%) gave a reaction as smooth as that with a saturated solution of the fully deprotonated nucleophile. Lowering the amount of anionic dimethyl malonate to 1% resulted in low yields even after prolonged irradiation.



Scheme 1. Molybdenum- and palladium-catalyzed allylic alkylation.

The molybdenum(0)-catalyzed alkylation also worked on a solid phase (TentaGel-OH, 99% *ee*, Scheme 2). Unfortunately, only low and variable overall yields were obtained (8–34% of **2a**).

Performing the microwave reaction with [$Mo(CO)_6$] in the absence of **3** resulted in a very low yield (<3%) of **2a** (major) along with **2b** (minor). The amount of product was too low to make an accurate estimate of the regioselectivity. Omitting [$Mo(CO)_6$] but otherwise using identical conditions provided no detectable quantities of the internally alkylated isomer **2a**. Instead, a very low yield of the terminally alkylated product

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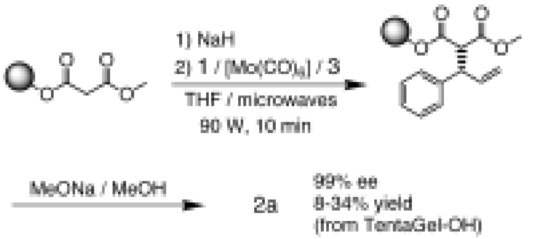
Supporting information for this article is available on the WWW under http://www/wiley-vch.de/home/angewandte/ or from the author.

Table 1. Microwave-heated molybdenum(0)-catalyzed asymmetric allylic alkylation of **1** under air.[a]

Entry	Power [W]	Time [min]	Solvent	Yield[b] (**2a**) [%]	Ratio[c] (**2a**:**2b**)	*ee*[d] [%]	TOF[e] [h^{-1}]
1	60	9	THF	86[f]	18:1	98	160
2	90	6	THF	86[f, g]	17:1	98	240
3	120	5	THF	86[f]	19:1	98	280
4	250	5	THF	87[f]	19:1	98	280
5	500	4	THF	85[f, h]	19:1	95	350
6	120	6	DME	92	22:1	98	240
7	130	7	dioxane	94	28:1	98	220
8	22 °C	20 d	THF	< 1[i]	n.d.[k]	n.d.	n.d.
9	80 °C	2 d	THF	11[f, i]	17:1	n.d.	0.07
10	165 °C	6	THF	59[f, i, j]	11:1	98	160
11	180 °C	6	THF	70[f, i, j]	16:1	98	190
12	160 °C	7	dioxane	67 %[i, j]	28:1	98	160

[a] Reactions were performed in solvent (2.5 mL) with **1** (0.21 M; 0.53 mmol), nucleophile (110 mol %), [Mo(CO)$_6$] (4 mol %), **3** (5 mol %), and BSA (120 mol %). Selected combinations of power and irradiation time (Microwell 10). [b] Determined by GC-MS with 2,3-dimethylnaphthalene as internal standard. [c] Determined by GC-MS with individual response factors for **2a** and **2b**. [d] Values from 2–6 reactions measured by repeated chiral HPLC (Daicel Chiracel OD-H, isohexane/2-propanol 99/1; 0.5 mL min^{-1}). [e] TOF = turnover frequency (number of catalytic cycles per unit time). [f] Small amounts (~6 %) of silylated cinnamyl alcohol were detected. [g] Yield of isolated product. [h] Noncontinuous heating; see Supporting Information. [i] Starting material remained. [j] Prolonged reaction time did not lead to higher yields. [k] n.d. = not determined.



Scheme 2. Solid-phase molybdenum(0)-catalyzed allylic alkylation.

2b was obtained, and this indicates a very slow, noncatalytic A · D (S$_N$2) path. The yield of **2b** in the latter experiment was much lower than that obtained with the Mo/**3** catalyst; hence, this implies an Mo/**3**-catalyzed route to **2b**.

Employing palladium(0)/PPh$_3$ as catalyst instead of Mo/**3** led to complete conversion of **1** into mainly the opposite regioisomer **2b** (Scheme 1; **2a**:**2b** = 1:13, 73 % yield of **2b**).[2]

Despite the high temperatures attained by microwave heating (up to 220 °C, Figure 1) the excellent enantiomeric purity (98 % *ee*, Table 1) of product **2a** remained constant. Therefore, we assume that ligand **3** is strongly bound to molybdenum(0).[7] The high temperatures are not only due to increased boiling points at elevated pressure, but also to a significant contribution from sustained superheating. Superheating phenomena have been well documented under microwave heating, even when open vessels are utilized, and constitute one of its main advantages.[8] In the case of pure, microwave-transparent 1,4-dioxane,[9] the microwave energy slowly heats the Duran tube, and this results in conductive heating of the solvent.

The microwave control experiments with pure THF and 1,4-dioxane furnished temperature profiles with lower temperature at every point relative to the reaction mixtures (Figure 1). The added substances, ionic or nonionic, must therefore contribute to the overall temperature profile when running the reaction.[10] Also, as is apparent from Table 1, the yields from the oil-bath experiments are lower than those of the corresponding microwave-heated reactions, and they did not reach full conversion.[11] This raises the question whether microwave-induced "hot-spots" exert an influence at the molecular level.[10] It seems reasonable that when the substrate molecules act as "molecular radiators" in channeling energy from microwave radiation to bulk heat their

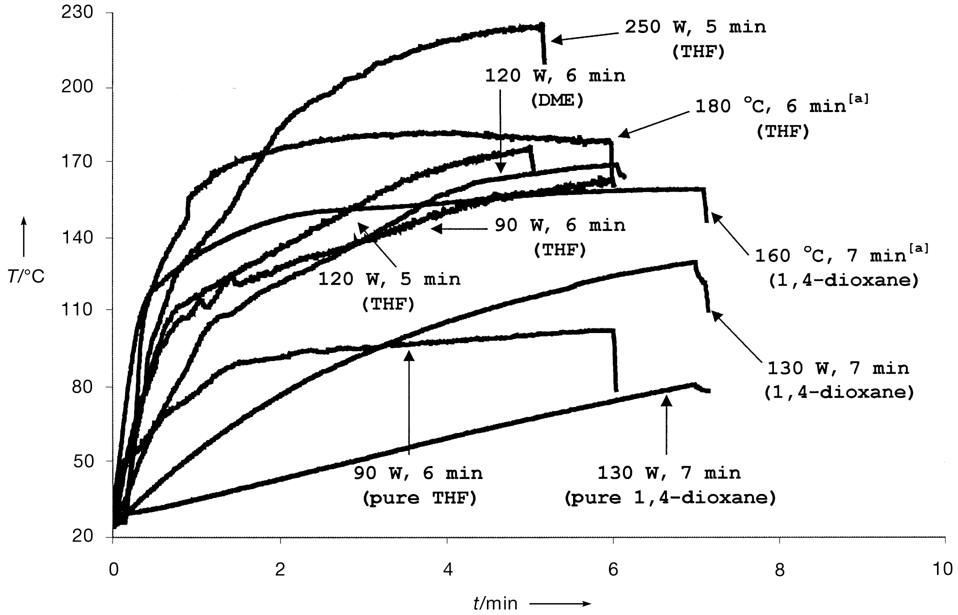


Figure 1. Selected temperature profiles for the microwave-heated, molybdenum(0)-catalyzed asymmetric allylic alkylations. Temperature profiles were recorded with a NoEMI-TS Reflex (Nortech Fibronic, Québec, Canada) equipped with a temperature-sensitive fluoroptic probe (TPP-01-M2.5-A, Nortech Fibronic). The probe was positioned at the bottom of the reaction tube. Sampling rate was 3 Hz. The reaction mixtures were efficiently cooled in water at room-temperature after completed irradiation. [a] Oil-bath heating.

reactivity might be enhanced.[12] In addition, the beneficial impact of microwave irradiation can be attributed to the instant, internal heat-transfer mode, as opposed to conventional heat transfer from the walls that is characteristic of traditional heating devices.[13] However, the origin of the increased efficiency in performing metal-catalyzed asymmetric high-temperature alkylations with focused microwave heating requires further investigation.

In conclusion, we have demonstrated a synthetically useful and easily handled microwave protocol for fast and selective molybdenum(0)-catalyzed allylic alkylation. The former sensitive reaction procedure has been transformed into a robust, air-stable, one-step procedure employing the inexpensive and stable precatalyst [Mo(CO)$_6$] in low concentration.

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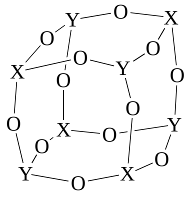
A Novel Borosilicate Cage Compound with an Incomplete B_4Si_4 Cube Structure: [(tBuSi)$_4$(CH$_2$=CHC$_6$H$_4$B)$_4$O$_{10}$]**

Lorraine A. Neville, Trevor R. Spalding,* and
George Ferguson

Recently there has been a proliferation of cube-based cages in which a variety of main group elements occupy corner sites and oxygen atoms bridge the main group atoms. Many "cubic" sections of the cages have the general formula $X_4Y_4O_{12}$ and adopt the double four-ring (D4R) (4-4) structure **1**. The positioning of the X and Y atoms at alternate corners is noteworthy and has been observed with various combinations of Group 13, 14, and 15 elements including those with X = Si and Y = Al,[1] Ga,[2] or In[2b, 3] and those with X = P and Y = B,[4] Al,[5] or Ga.[6] These compounds are related to silsesquioxanes (X = Y = Si in **1**) which have been studied extensively.[7] One aim in developing the chemistry of these compounds is to use them as building blocks in the construction of more complex materials, possibly zeolites or catalyst supports. Another aim is to develop their applications in microelectronics as interlevel low *k* dielectrics. In the latter respect, silsesquioxanes have already attracted the attention of several industries including microelectronics manufacturers.[8]



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Relatively little work has been done on the chemistry of molecular borosilicates. Established borosilicate cages which have been reported are [tBuSi{O(BC$_6$H$_4$Br)O}$_3$SitBu] (**2**)[9] with a {B$_3$Si$_2$O$_6$} cage, [B(OSiPh$_2$OSiPh$_2$O)$_3$B] (**3**)[10] with a {B$_2$Si$_6$O$_9$} cage, and the silsesquioxane-based borosilicates [{(*cyclo*-C$_6$H$_{11}$Si)$_7$BO$_{12}$}$_2$][11] and [{(*cyclo*-C$_6$H$_{11}$Si)$_8$O$_{13}$(B*n*-Bu)],[12] and anionic silsesquioxane-borato complexes of the types [R$_7$Si$_8$O$_{12}${OB(C$_6$F$_5$)$_3$}]$^-$ and [R$_7$Si$_7$O$_9$(OH)$_2$-{OB(C$_6$F$_5$)$_3$}]$^-$.[13] Whereas all the silsesquioxane-based compounds were synthesized from preformed silsesquioxane fragments and single boron-containing reagents, compounds **2** and **3** were synthesized from reagents containing only single silicon and boron. In the case of **2**, the reagents were tBuSi(OH)$_3$ and a boronic acid, and for **3** the reagents were Ph$_2$Si(OH)$_2$ and boric acid. We have now used single boron- and silicon-containing reagents to synthesize a new type of cube-based compound with both three- and four-coordinate corner sites. The compound [(tBuSi)$_4$(CH$_2$=CHC$_6$H$_4$B)$_4$O$_{10}$]

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