

## Visible-Light-Promoted *Wohl–Ziegler* Functionalization of Organic Molecules with *N*-Bromosuccinimide under Solvent-Free Reaction Conditions

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The visible-light-induced transformation of toluenes with *N*-bromosuccinimide (NBS) under solvent-free reaction conditions (SFRC) was studied. The reaction took place in spite of the very restricted molecular motion; toluenes could be regioselectively converted to benzyl bromides. Selective radical-chain reactions with NBS were carried out in liquid/liquid and in solid/solid systems; furthermore, reactions could be performed in the presence of air. The radical scavenger TEMPO (=2,2,6,6-tetramethylpiperidin-1-yloxy) completely suppressed the side-chain bromination of toluenes with NBS under SFRC. Electron-withdrawing groups decreased the reactivity of the toluenes, and the *Hammett* reaction constant  $\rho^+ = -1.7$  indicated involvement of polar radical intermediates with electrophilic character.

**Introduction.** – In the context of promoting a sustainable development, the concept and principles of green chemistry, which emerged a decade ago [1], have had a considerable effect on modern research and scientific trends in chemistry, especially in organic chemistry. To diminish the pollution of the environment, the development of alternative methodologies and protocols for the transformation of organic compounds is becoming one of the major challenges for organic chemists, while improvement of atom economy, reduction of health and safety risks, waste minimization, and cost efficiency of chemical processes are their principal components. Reusable reaction media, such as ionic liquids or a fluorous phase, is an often used alternative, but in the scope of green chemistry ‘the best solvent is no solvent’ [2]. Examples of solvent-free fluorination [3], chlorination [4], iodination [5], and bromination [6–8] are presented in both old and recent reports.

Achieving selectivity of radical-chain reactions in dilute solution is often not a trivial task, while an even more delicate situation in photoinduced reactions under solvent-free reaction conditions (SFRC) could be anticipated. Many UV- or X-ray-induced [2 + 2] cycloadditions and other photoinitiated transformations are known under SFRC [2b], but reactions frequently involve one solid reactant and take place in a single crystal (photodimerization for example), whereas reports on the reactivity of two discrete solids in a visible-light-induced transformation appear to be rare. A few examples of thermal and microwave-initiated *Wohl–Ziegler* brominations under SFRC have been published [9], with the main focus on the synthetic method. However, photoinduced radical reactions with NBS under SFRC still remain unexplored.

*N*-Bromosuccinimide (NBS) is one of the basic reagents in organic chemistry, and the *Wohl–Ziegler* bromination [10] has been one of the most extensively studied reactions [11]. Transformation of organic molecules with NBS was studied under thermal [12], photochemical [13], sonochemical [14], and microwave reaction conditions [15], as well as in H<sub>2</sub>O [16], in ionic liquids [17], and in supercritical CO<sub>2</sub> [18]. Chain-carrying radicals (succinimidyl or bromine) were a matter of controversy for years [19]. We were interested in the question about the occurrence of selective reactions under SFRC. Another issue is how product formation influences the conversion of the remaining reactant since the product could cover or coat the surface of the starting material. Mercury or strong tungsten lamps, hazardous solvents like CCl<sub>4</sub>, and a dry, inert atmosphere with air carefully removed are often regarded as ‘normal’ conditions for radical-chain reactions (see, *e.g.*, an exception in [20]). The question arises whether it is possible to perform radical reactions with a 40 W tungsten lamp in the presence of air without an inert-gas atmosphere. Is it necessary to employ a radical initiator? What types of intermediates are likely to be involved in such a transformation? These were the issues investigated in this study.

**Results and Discussion.** – NBS is known to be a light-sensitive molecule, and the commercial reagent is always slightly yellow due to the presence of traces of Br<sub>2</sub>, and this could influence the stability of NBS, but it is unclear how the system behaves under SFRC. Therefore, we initially tested the stability of crystallized NBS under illumination with a 40 W bulb as detailed in *Table 1*. Irradiation in an open flask for 16 h resulted in only 2% conversion to succinimide; this rose to 6–11% in a stoppered flask or with small amounts of solvent, to 14–21% in solution, and to 100% with added MeOH or in MeOH solution. Clearly, NBS is most stable under solvent-free open-flask conditions, Br<sub>2</sub> not being generated, and another reaction partner is needed to induce electron flow.

Table 1. *Stability of NBS under Various Conditions under Illumination with a 40 W Tungsten Lamp*

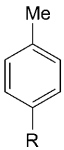
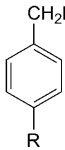
| Reaction conditions <sup>a)</sup>          | Conversion [%] <sup>b)</sup> |
|--------------------------------------------|------------------------------|
| SFRC, open flask <sup>c)</sup>             | 2                            |
| added H <sub>2</sub> O (1 equiv.)          | 6                            |
| SFRC, stoppered flask <sup>c)</sup>        | 8                            |
| SFRC, Br <sub>2</sub> (vap.) <sup>c)</sup> | 9                            |
| added CCl <sub>4</sub> (1 equiv.)          | 11                           |
| 0.1M NBS in H <sub>2</sub> O               | 14                           |
| 0.1M NBS in CCl <sub>4</sub>               | 21                           |
| added MeOH (1 equiv.)                      | 100                          |
| 0.1M NBS in MeOH                           | 100                          |

<sup>a)</sup> 0.2 mmol of NBS irradiated for 16 h at 36°. <sup>b)</sup> Determined by <sup>1</sup>H-NMR. <sup>c)</sup> SFRC = solvent-free reaction conditions.

First, we studied the effect of the aggregate state of the following substituted toluenes on bromination under SFRC: 4-(*tert*-butyl)toluene (**1a**; liquid), 2,3,4,5,6-pentafluorotoluene (**3**; liquid), and 4-nitrotoluene (**1b**; solid). It was not clear whether

a photoinitiated radical-chain reaction in liquid/solid and solid/solid systems under SFRC could take place, but [9c] provides an indication for this. The reactions were first tested in the dark and, as anticipated, none of them took place, not even in the presence of dibenzoyl peroxide at 60°. In the photoinitiated reactions, stirring obviously facilitated the transformation to **2a** in the liquid/solid system **1a**/NBS (*Table 2, Entries 1 and 2*); on the other hand, the reaction could take place without stirring but required a longer reaction time *t* (*Entry 3*). In a solid/solid system, stirring is of much greater relevance than in a liquid/solid system due to the great difference in molecular motion (*Entries 6 and 7*). A remarkable effect of the substituent R or the F-atoms was noted in the case of no stirring (*Entries 3, 6, and 10*), in contrast to an only moderate effect in the case of stirring (*Entries 4, 7, and 11*). An electron-releasing group favored the reaction much more than an electron-withdrawing group, since 2,3,4,5,6-pentafluorotoluene (**3**) was the least reactive among these substrates ( $\rightarrow$  **4**).

Table 2. Effect of Substituent, Aggregate State, and Reaction Conditions on Photoinduced Benzylic Bromination of Toluenes with NBS under SFRC

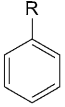
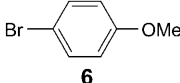
| <div style="display: flex; align-items: center; justify-content: center;"> <div style="text-align: center;">  <p><b>1a</b> R = <i>t</i>-Bu, liquid<br/> <b>1b</b> R = NO<sub>2</sub>, solid<br/> <b>3</b> C<sub>6</sub>F<sub>5</sub>Me, liquid</p> </div> <div style="margin: 0 20px; text-align: center;"> <math>\xrightarrow[\text{SFRC, 36}^\circ]{\text{NBS, } h\nu, 40 \text{ W}}</math> </div> <div style="text-align: center;">  <p><b>2a</b><br/> <b>2b</b><br/> <b>4</b> C<sub>6</sub>F<sub>5</sub>CH<sub>2</sub>Br</p> </div> </div> |           |                              |                                   |                   |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|------------------------------|-----------------------------------|-------------------|
| Entry                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Substrate | <i>t</i> [min] <sup>a)</sup> | Reaction conditions <sup>b)</sup> | Conversion [%]    |
| 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | <b>1a</b> | 160                          | B                                 | 0                 |
| 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |           | 160                          | A                                 | 36                |
| 3                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |           | 480                          | B                                 | 85 <sup>c)</sup>  |
| 4                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |           | 480                          | A                                 | 92 <sup>c)</sup>  |
| 5                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |           | 600                          | A                                 | 100 <sup>c)</sup> |
| 6                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | <b>1b</b> | 480                          | B                                 | 5                 |
| 7                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |           | 480                          | A                                 | 60 <sup>c)</sup>  |
| 8                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |           | 960                          | B                                 | 83 <sup>c)</sup>  |
| 9                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | <b>3</b>  | 960                          | A                                 | 96 <sup>c)</sup>  |
| 10                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |           | 480                          | B                                 | 4                 |
| 11                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |           | 480                          | A                                 | 40                |
| 12                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |           | 1080                         | A                                 | 100 <sup>c)</sup> |

<sup>a)</sup> *t*, Reaction time. <sup>b)</sup> A, under stirring; B, no stirring. <sup>c)</sup> Accompanied by the CHBr<sub>2</sub> derivative: *Entry 3*, 9%; *Entry 4*, 8%; *Entry 5*, 10%; *Entry 7*, 4%; *Entry 8*, 4%; *Entry 9*, 4%; and *Entry 12*, 6%.

Next, beside toluene (**1c**), we chose anisole (**5**) and acetophenone (**7**) as substrates (*Table 3*). Anisole is sensitive to ring substitution, also under radical or cation-radical conditions [21], while acetophenone could be halogenated *via* the enol form. In the light-induced bromination, **1c** could readily be converted to benzyl bromide (**2c**; 87%), **5** exclusively furnished 4-bromoanisole (**6**), while **7** was  $\alpha$ -brominated ( $\rightarrow$  **8a**); these

transformations did not take place in the absence of light (*Entries 1, 4, and 7*). The transformation of toluene (**1c**) in the presence of the radical scavenger TEMPO (=2,2,6,6-tetramethylpiperidin-1-yloxy) was completely suppressed (*Entry 3*); thus benzyl bromide (**2c**) was formed in a radical process. A significantly lower effect was noted for **5** and **7** (*Entries 6 and 9*).

Table 3. Effect of the Substituent (Me, MeO, or MeCO) on the Type of Reaction with NBS under SFRC

| <div style="display: flex; align-items: center; justify-content: center;"> <div style="text-align: center; margin-right: 20px;">  <p><b>1c</b> R = Me<br/><b>5</b> R = MeO<br/><b>7</b> R = MeCO</p> </div> <div style="text-align: center; margin-right: 20px;"> <math>\xrightarrow[\text{SFRC, 36}^\circ]{\text{NBS, } h\nu, 40 \text{ W}}</math> </div> <div style="display: flex; flex-direction: column; align-items: center;"> <div style="display: flex; justify-content: space-around; width: 100%;"> <div style="text-align: center;"> <math>\text{PhCH}_2\text{Br}</math><br/><b>2c</b> </div> <div style="text-align: center;"> <math>+</math> </div> <div style="text-align: center;"> <math>\text{PhCHBr}_2</math><br/><b>2cc</b> </div> </div> <div style="text-align: center; margin: 10px 0;">  <p><b>6</b></p> </div> <div style="display: flex; justify-content: space-around; width: 100%;"> <div style="text-align: center;"> <math>\text{PhCOCH}_2\text{Br}</math><br/><b>8a</b> </div> <div style="text-align: center;"> <math>+</math> </div> <div style="text-align: center;"> <math>\text{PhCOCHBr}_2</math><br/><b>8aa</b> </div> </div> </div> </div> |           |                            |                                 |                |                           |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|----------------------------|---------------------------------|----------------|---------------------------|
| Entry                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Substrate | <i>t</i> [h] <sup>a)</sup> | Reaction conditions             | Conversion [%] | Selectivity <sup>b)</sup> |
| 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | <b>1c</b> | 9.5                        | dark                            | 0              |                           |
| 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | <b>1c</b> | 9.5                        | <i>hν</i>                       | 94             | 87:13                     |
| 3                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | <b>1c</b> | 9.5                        | <i>hν</i> , TEMPO <sup>c)</sup> | 0              |                           |
| 4                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | <b>5</b>  | 18                         | dark                            | 0              |                           |
| 5                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | <b>5</b>  | 18                         | <i>hν</i>                       | 100            |                           |
| 6                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | <b>5</b>  | 18                         | <i>hν</i> , TEMPO <sup>c)</sup> | 74             |                           |
| 7                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | <b>7</b>  | 16                         | dark                            | 2              |                           |
| 8                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | <b>7</b>  | 16                         | <i>hν</i>                       | 73             | 68:32                     |
| 9                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | <b>7</b>  | 16                         | <i>hν</i> , TEMPO <sup>c)</sup> | 62             | 88:12                     |

<sup>a)</sup> *t*, Reaction time. <sup>b)</sup> For **1c**, **2c/2cc**; for **7**, **8a/8aa**. <sup>c)</sup> TEMPO (0.25 equiv.) was added.

Next, we examined the progress of bromination of **1c**, **5**, and **7**, and various induction periods were observed (*Fig. 1*). Further, we investigated the role of the substituent on the benzylic C-atom, *i.e.*, the behavior of **1c** vs. **11a** vs. **11b**, and the role of the structure of the dimethylbenzenes **11c–11e** on the functionalization with NBS; the results are shown in *Table 4*. A crucial influence on the reaction rate was found; the nitrile group in **11a** (*Entry 3*; → **12a**) contributed significantly to retardation, while the H-atom or the Me group in **1c** and **11b** (*Entries 1 and 5*) had a beneficial effect on the rate of conversion (→ **2c** and **12b**, resp.). This indicates that the benzyl radical has principally an electrophilic character. In contrast, illumination of benzyl ethyl ether (PhCH<sub>2</sub>OEt) under SFRC led to fragmentation, and a complex mixture was isolated. However, benzaldehyde (PhCHO) was the main product, and a similar observation was noted for the reaction of the related benzyl methyl ether (PhCH<sub>2</sub>OMe) in CCl<sub>4</sub> [22]. Further, we established that the only reactive sites in the dimethylbenzenes **11c–11e** are the Me groups (→ **12c–12e**), and no ring functionalization occurred. In contrast to toluene (**1c**), no (dibromomethyl)-substituted products were obtained. The relative ratio of the CH<sub>2</sub>Br vs. the bis(CH<sub>2</sub>Br) derivative was practically independent of the structure of the molecule (*Table 4, Entries 8–12*). Transformation of dimethylbenzenes with NBS under photoinduced SFRC obviously takes place with a higher

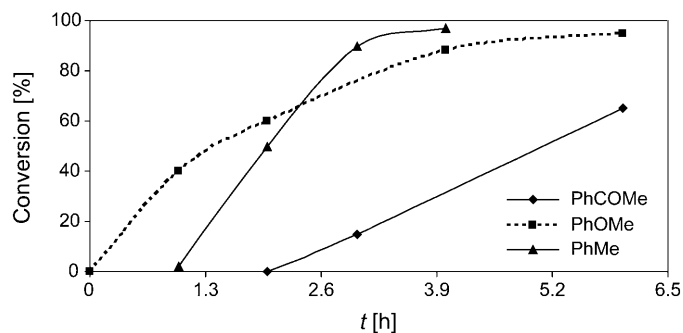
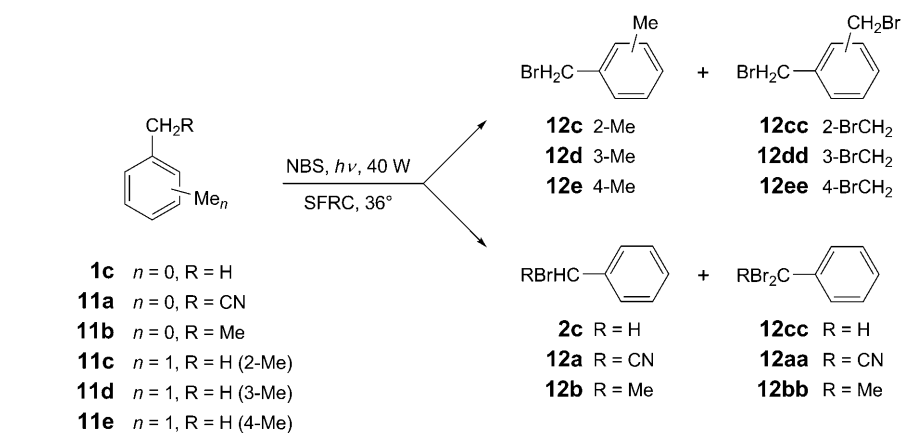


Fig. 1. The course of photoinduced bromination with NBS under SFRC: ring- vs. 'benzylic'- vs.  $\alpha$ -carbonyl-substitution

Table 4. Effect of Substituents on Reactivity and Selectivity in the Photoinduced Bromination of Toluenes and Xylenes with NBS under SFRC



| Entry | Substrate  | Reaction time [h] | Conversion [%] | Selectivity <sup>a)</sup> |
|-------|------------|-------------------|----------------|---------------------------|
| 1     | <b>1c</b>  | 3                 | 90             | 85 : 15                   |
| 2     | <b>1c</b>  | 6                 | 94             | 87 : 13                   |
| 3     | <b>11a</b> | 3                 | 23             | > 99                      |
| 4     | <b>11a</b> | 21                | > 99           | > 99                      |
| 5     | <b>11b</b> | 3                 | 91             | > 99                      |
| 6     | <b>11b</b> | 5                 | > 99           | 95 : 5 <sup>b)</sup>      |
| 7     | <b>11c</b> | 3                 | 70             | > 99                      |
| 8     | <b>11c</b> | 6                 | 89             | 87 : 13                   |
| 9     | <b>11d</b> | 3                 | 79             | 85 : 15                   |
| 10    | <b>11d</b> | 6                 | 87             | 82 : 18                   |
| 11    | <b>11e</b> | 3                 | 84             | 87 : 13                   |
| 12    | <b>11e</b> | 6                 | 86             | 86 : 14                   |

<sup>a)</sup> For **1c**, **11a**, and **11b** mono- vs. dibromination (**2c/2cc**, **12a/12aa**, and **12b/12bb**); for **11c–11e** CH<sub>2</sub>Br vs. bis(CH<sub>2</sub>Br) (**12c–12e/12cc–12ee**). <sup>b)</sup> 5% of 2-bromo-1-phenylethanone was formed.

selectivity in comparison with microwave-induced bromination [9b], bromination in H<sub>2</sub>O with Br<sub>2</sub> [23], or bromination in the H<sub>2</sub>O<sub>2</sub>/HBr system [24], while no dibromination was noted in the microwave-assisted reaction under SFRC [25]. Functionalization of substrates possessing secondary and primary, or tertiary and primary H-atoms like in 4-ethyltoluene and 4-isopropyltoluene resulted in complex reaction mixtures.

To further establish the role of the reaction conditions, 4-(*tert*-butyl)toluene (**1a**) and 4-nitrotoluene (**1b**) were targeted (Table 5). Recently, a remarkable rate acceleration of organic reactions was demonstrated after preorganization of the reactants in a solvent, which was then immediately evaporated [26]. Similarly **1a** and **1b** were separately preorganized with NBS, either in petroleum ether/CH<sub>2</sub>Cl<sub>2</sub> or in MeOH. Preorganization of **1a** in petroleum ether/CH<sub>2</sub>Cl<sub>2</sub> had a very beneficial effect on the reaction rate (Table 5, Entries 1 and 3), while it had a completely opposite effect on the transformation of **1b** (Table 5, Entries 1 and 3). Obviously, this preorganization enhanced the intermolecular contact in the case of **1a**, whereas it contributed to the separation of the reactants in the case of **1b**. In the latter case, during evaporation of petroleum ether/CH<sub>2</sub>Cl<sub>2</sub>, the more volatile CH<sub>2</sub>Cl<sub>2</sub> evaporated before the petroleum ether, which induced selective crystallization of NBS, while **1b** was still in solution and crystallized last. The difference in reactivity in the solid/solid system could thus be attributed to consecutive crystallization of the reactants. Preorganization of **1a** and NBS in MeOH also had an advantageous effect, but an even more dramatic enhancement was noted in the case of **1b** (Entry 4). Both reactants started to crystallize from the solution during the evaporation of MeOH at about the same time, which brought the molecules into much more intimate contact, thus enhancing the reactivity. Recently, an exceptional rate enhancement in solid/solid systems was established when a small amount of solvent vapor was present [27]. As evident from Table 5, the addition of a small quantity of MeOH was exceedingly beneficial for both **1a** and **1b** (Entry 5). On the other hand, the effect of deionized H<sub>2</sub>O was not uniform,

Table 5. Effect of Reaction Conditions, Substituent, and Aggregate State of 4-(*tert*-Butyl)toluene (**1a**) and 4-Nitrotoluene (**1b**) on Photoinduced Benzylic Bromination with NBS under SFRC at 36°

| Entry | Reaction conditions <sup>a)</sup>                                         | <i>t</i> [min]; conversion [%] <sup>b)</sup> |                                  |
|-------|---------------------------------------------------------------------------|----------------------------------------------|----------------------------------|
|       |                                                                           | <b>1a</b> (R = <i>t</i> -Bu)                 | <b>1b</b> (R = NO <sub>2</sub> ) |
| 1     | SFRC                                                                      | 160; 36                                      | 300; 15                          |
| 2     | SFRC                                                                      | 360; 90                                      | 960; 96                          |
| 3     | PO (petroleum ether/CH <sub>2</sub> Cl <sub>2</sub> ), SFRC <sup>c)</sup> | 160; 86                                      | 300; 0                           |
| 4     | PO (MeOH), SFRC <sup>c)</sup>                                             | 160; 66                                      | 300; 82                          |
| 5     | added MeOH (1 equiv.)                                                     | 160; 90                                      | 300; 42                          |
| 6     | added H <sub>2</sub> O (1 equiv.)                                         | 160; 50                                      | 300; 8                           |
| 7     | 0.1M <b>1</b> in MeOH                                                     | 160; 30                                      | 300; traces                      |
| 8     | 0.1M <b>1</b> in Et <sub>2</sub> O                                        | 160; traces                                  | 300; traces                      |
| 9     | SFRC, TEMPO <sup>d)</sup>                                                 | 160; 0                                       | 300; 0                           |

<sup>a)</sup> SFRC = solvent-free reaction conditions. <sup>b)</sup> *t* = reaction time. <sup>c)</sup> PO = preorganization, *i.e.*, **1** and NBS were dissolved in solvent (MeOH or petroleum ether/CH<sub>2</sub>Cl<sub>2</sub>), and the solvent was evaporated.

<sup>d)</sup> TEMPO (0.25 equiv.) was added.

and its role was much more limited. Photoinduced reactions in solution are clearly less effective in comparison with reactions under SFRC (*Entries 7 and 8*). TEMPO, regardless of the aggregate state, completely suppressed the benzylic bromination, suggesting that radicals are the intermediates (*Entry 9*). From *Table 5*, it can be summarized that photoinitiated reactions with NBS under SFRC are very sensitive to reaction conditions. From *Tables 2 and 5*, the rather diverse reactivity of **1a** and **1b** is evident, but their inherent reactivity is yet to be estimated. Reaction profiles of **1a–1c** and **3** in the reaction with NBS were determined (*Fig. 2*). Induction periods differed considerably and rose with decreasing reactivity of the substrates. Toluene (**1c**) was more reactive than 4-(*tert*-butyl)toluene (**1a**), reflecting the fact that the motion of reactants is a more crucial parameter than electronic effects under SFRC. The 2,3,4,5,6-pentafluorotoluene (**3**) had an induction period which was one hour longer than that of 4-nitrotoluene (**1b**) and exhibited a strong electronic effect on the radical-chain reaction. Such an interference of effects prevents the definite prediction of reactivity, but in general, solid substrates with electron-withdrawing groups are less reactive than liquid substrates possessing electron-releasing groups.

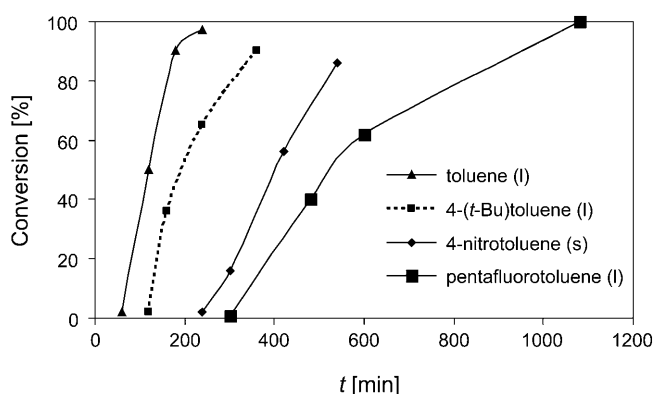


Fig. 2. The effect of aggregate state and substituents on the course of the photobromination of toluenes with NBS under SFRC

In addition, we examined the role of the brominating agent (NBS vs.  $\text{Br}_2$ ) and of the structure of the deactivated toluenes on benzylic bromination (*Table 6*). The 4-nitrotoluene (**1b**) gave the highest conversion in reaction with NBS; the liquid nitrotoluenes **13a** and **13b** exhibited rather diverse results (*Entries 1, 5, and 9*). These substantial differences indicate that a nitro group in close proximity (*ortho* position) to the reaction center acts as an inhibitor. A similar reactivity in liquid/liquid (**13a** or **13b**) and in solid/liquid systems (**1b**) was established in the bromination with  $\text{Br}_2$  under SFRC, furnishing the related benzyl bromides **14a**, **14b**, and **2b**. Bromination with NBS of the deactivated toluenes, regardless of their aggregate state and reactivity, took place *via* radical intermediates (*Entries 2, 6, 12, and 16*). Reaction intermediates in the case of bromination with  $\text{Br}_2$  did not appear to be so invariable (*Entries 8, 14, and 18*).

The *Hammett* correlation analysis is a very convenient mechanistic tool for the evaluation of the transition state, character, and polarity of intermediates, but kinetic

Table 6. Effect of Structure and Aggregate State of Deactivated Toluenes and of the Reagent on Photoinduced Bromination under SFRC

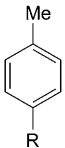
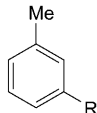
|    | Substrate      | R                        | Reagent         | Additive | Reaction time [h] | Conversion [%]    |
|----|----------------|--------------------------|-----------------|----------|-------------------|-------------------|
| 1  | <b>1b</b> (s)  | 4-NO <sub>2</sub>        | NBS             | –        | 16                | 96                |
| 2  |                |                          | NBS             | TEMPO    | 16                | 0                 |
| 3  |                |                          | Br <sub>2</sub> | –        | 16                | 75                |
| 4  |                |                          | Br <sub>2</sub> | TEMPO    | 16                | 0                 |
| 5  | <b>13a</b> (l) | 3-NO <sub>2</sub>        | NBS             | –        | 16                | 83 <sup>a</sup> ) |
| 6  |                |                          | NBS             | TEMPO    | 16                | 0                 |
| 7  |                |                          | Br <sub>2</sub> | –        | 16                | 33                |
| 8  |                |                          | Br <sub>2</sub> | TEMPO    | 16                | 0                 |
| 9  | <b>13b</b> (l) | 2-NO <sub>2</sub>        | NBS             | –        | 16                | 16                |
| 10 |                |                          | Br <sub>2</sub> | –        | 16                | 8                 |
| 11 | <b>1c</b>      | H                        | NBS             | –        | 0.83              | 97                |
| 12 |                |                          | NBS             | TEMPO    | 0.83              | 0                 |
| 13 |                |                          | Br <sub>2</sub> | –        | 0.83              | 69 <sup>b</sup> ) |
| 14 |                |                          | Br <sub>2</sub> | TEMPO    | 0.83              | 22 <sup>b</sup> ) |
| 15 | <b>3</b>       | 2,3,4,5,6-F <sub>5</sub> | NBS             | –        | 18                | 100               |
| 16 |                |                          | NBS             | TEMPO    | 18                | 0                 |
| 17 |                |                          | Br <sub>2</sub> | –        | 18                | 100               |
| 18 |                |                          | Br <sub>2</sub> | TEMPO    | 18                | 100               |

<sup>a</sup>) 17% of CHBr<sub>2</sub> derivative was formed. <sup>b</sup>) Refers only to benzylic bromination, ring bromination takes place as well.

studies under SFRC are very scarce. Benzylic bromination of toluene derivatives conducted in benzene [19c][19e] exhibited  $\rho = -1.46$ , in CCl<sub>4</sub>  $\rho = -1.38$  [19d], and in CH<sub>2</sub>Cl<sub>2</sub>  $\rho = -1.41$  [28]. We examined the photoinduced benzylic bromination of the 3- and 4-substituted toluenes **1b**, **13a**, and **15** under SFRC with NBS. In our case, despite the heterogeneous reaction mixture, and even though only neat reactants were mixed and the resulting mixture was illuminated with a 40 W tungsten lamp, a surprisingly good agreement ( $r = 0.95$ ) was obtained (Fig. 3 and Table 7). The best correlation was obtained with  $\sigma^+$  parameters ( $\rho = -1.73$ ,  $T 36^\circ$ ) which indicates that the transition state is similarly polar as that in solution, suggesting the involvement of electron-deficient, electrophilic radical intermediates in the charge-separated dipolar transition state.

**Conclusions.** – In this report, we showed that in visible-light-induced (40 W tungsten lamp) radical-chain bromination of toluenes with NBS under SFRC, reaction

Table 7. Hammett-Correlation Analysis of the Benzylic Bromination with NBS of Toluene Derivatives under SFRC<sup>a)</sup>

|       |            |  |            |  |                |
|-------|------------|-----------------------------------------------------------------------------------|------------|-----------------------------------------------------------------------------------|----------------|
|       |            | <b>1b,c</b>                                                                       |            | <b>13a</b>                                                                        |                |
|       |            | <b>15a – c</b>                                                                    |            | <b>15d – g</b>                                                                    |                |
| Entry | Substrate  | R                                                                                 | $\sigma^+$ | $k_R/k_H^b)$                                                                      | $\log k_R/k_H$ |
| 1     | <b>1c</b>  | 4-H                                                                               | 0          | 1                                                                                 | 0              |
| 2     | <b>15a</b> | 4-F                                                                               | – 0.073    | 0.781                                                                             | – 0.11         |
| 3     | <b>15b</b> | 4-Cl                                                                              | 0.11       | 0.812                                                                             | – 0.09         |
| 4     | <b>15c</b> | 4-Br                                                                              | 0.15       | 0.698                                                                             | – 0.16         |
| 5     | <b>15d</b> | 3-F                                                                               | 0.352      | 0.273                                                                             | – 0.56         |
| 6     | <b>15e</b> | 3-Cl                                                                              | 0.399      | 0.219                                                                             | – 0.66         |
| 7     | <b>15f</b> | 3-Br                                                                              | 0.405      | 0.233                                                                             | – 0.63         |
| 8     | <b>15g</b> | 3-CF <sub>3</sub>                                                                 | 0.52       | 0.086                                                                             | – 1.07         |
| 9     | <b>13a</b> | 3-NO <sub>2</sub>                                                                 | 0.674      | 0.037                                                                             | – 1.44         |
| 10    | <b>1b</b>  | 4-NO <sub>2</sub>                                                                 | 0.79       | 0.069                                                                             | – 1.16         |

<sup>a)</sup> 0.3 mmol of NBS and 0.3 mmol of toluene (**1c**) (Entries 2–7) or 0.3 mmol of 3-bromotoluene (**15f**) (Entries 8–10) as references and 0.3–0.6 mmol of another substrate, stirring and illumination with a 40 W lamp at 36° to full consumption of NBS. <sup>b)</sup> The relative reactivity of the substituted toluenes was determined vs. toluene (as a reference). 1 Equiv. of toluene and 1 equiv. of substituted toluene and 1 equiv. of NBS were mixed and stirred, the reaction mixture was analyzed by NMR, and  $k_{rel}$  was obtained. In the case of toluenes possessing substantially different reactivity, 2 equiv. of less reactive substrate was taken. The difference in reactivity of 4-nitrotoluene and toluene, for example, was too high to obtain reliable  $k_{rel}$  in this way. For this reason, 3-bromotoluene (significantly less reactive than toluene) was taken as a second reference molecule for 3-nitrotoluene, 4-nitrotoluene, and 3-trifluoromethyltoluene. Relative reactivity of these three molecules vs. toluene was therefore determined indirectly, for example  $k(4\text{-NO}_2)/k(4\text{-H})$  was obtained from:  $k(3\text{-Br})/k(4\text{-H})$  and  $k(3\text{-Br})/k(4\text{-NO}_2)$ .

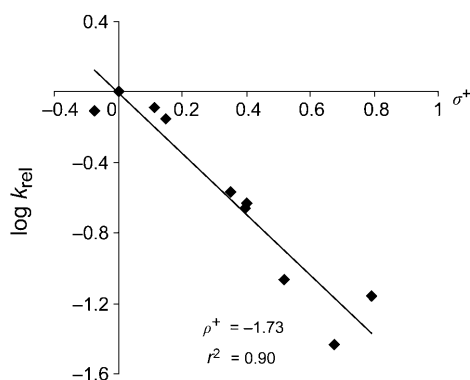


Fig. 3. Hammett linear free-energy relationship for photoinduced benzylic bromination of toluenes with NBS under SFRC

takes place in the presence of air, so no inert atmosphere is needed. Molecular migration is dramatically reduced; the aggregate state of the substrates plays an important role, but both liquid and solid toluenes could selectively be converted to the corresponding benzyl bromides. Ring bromination of anisole (**5**) and side-chain bromination of acetophenone (**7**) were observed under SFRC. The reactivity of toluenes depends on the substituents; electron-releasing groups facilitate, whereas electron-withdrawing groups decrease the reactivity. The inherent reactivity of substrates differs as well; the induction period is longer in the case of solids and electron-poorer substrates. The radical scavenger TEMPO completely suppresses side-chain bromination with NBS. Despite being a heterogeneous reaction system, a good *Hammett* free-energy relationship ( $r = 0.95$ ,  $\rho = -1.73 \sigma^+$ ) was obtained. It is suggested that substantial charge separation in the dipolar transition state is involved in the radical reaction under SFRC; reactions in solution exhibit a similar reaction course.

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### Experimental Part

**General.** Reactions were performed under air in ordinary flasks. Heterogeneous reaction mixtures (solid/liquid or solid/solid) under solvent-free-reaction conditions (SFRC) were stirred with a small stirring bar, and despite the fact that only a part of the reaction mixture was stirred (120–160 rpm), no problems were observed in the progress of the reaction. The experimental procedure for solid/liquid, solid/solid, and liquids was the same; NBS or  $\text{Br}_2$  was added to the substrate. Chemicals were obtained from commercial sources and distilled or crystallized if necessary. NBS was crystallized, solvents were used as received. An ordinary 40 W tungsten lamp was used throughout all the experiments, and the average reaction temp. was  $36^\circ$ . Blank experiments were performed in the dark at  $36^\circ$ . Crude reaction mixtures were directly subjected to column chromatography (CC). Conversions were determined by  $^1\text{H-NMR}$ , and yields of isolated product refer to pure products. All the products are known compounds, and their properties were in agreement with published data. Flash column chromatography (FC): silica gel 60 (63–200  $\mu\text{m}$ , 70–230 mesh ASTM; *Fluka*). TLC: *Merck-60-F<sub>254</sub>* plates; mixtures of light petroleum ether (b.p.  $40-60^\circ$ ) and  $\text{CH}_2\text{Cl}_2$ . NMR Spectra: *Bruker-Avance-300-DPX* instrument.

**Photoinduced Reactions with NBS or  $\text{Br}_2$  under SFRC. General Procedure.** To toluene (47 mg, 0.5 mmol; **1c**), NBS (98 mg, 0.55 mmol) was added, and the resulting mixture was subjected to stirring and illumination with a 40 W tungsten lamp until practically full conversion was achieved (4 h). After CC, benzyl bromide was obtained. The procedure is the same for other solid substrates.

**General Preorganization Procedure.** Substrate and NBS were dissolved in MeOH or in a petroleum ether/ $\text{CH}_2\text{Cl}_2$ , and the solvent was immediately evaporated at  $23^\circ$  under reduced pressure. The resulting mixture was exposed to illumination with a 40 W tungsten lamp.

**Measurement of Relative Rates in the Hammett Correlation Analysis: General Procedure.** The relative reactivities of substituted toluenes (*Fig. 3*) were determined by competitive reactions as follows: To a mixture of two substrates (reference and the examined substituted toluene, rel. ratio 1:1 or 1:2, depending on reactivity), NBS (1 equiv.) was added, and the mixture was stirred. The crude reaction mixture was analyzed by NMR. Relative reactivities expressed by relative rate factors  $k_R$  were calculated from the equation [19e]  $k_R = k_A/k_B = \log((A-X)/A)/\log((B-Y)/B)$ , derived from the *Ingold–Shaw* relation [29], where A and B are the amounts of starting material and X and Y the amounts of products derived from them. The relative rate factors thus obtained, collected in *Fig. 3* and *Table 7*, are the averages of at least three measurements; the average deviation of measurements was as follows: 4-F (10%), 4-Cl (2%), 4-Br (4%), 3-F (5%), 3-Cl (3%), 3-Br (5%), 3- $\text{CF}_3$  (3%), 3- $\text{NO}_2$  (10%), and 4- $\text{NO}_2$  (6%).

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