BEILSTEIN JOURNAL OF ORGANIC CHEMISTRY

Substituent-controlled construction of A_4B_2-hexaphyrins and A_3B-porphyrins: a mechanistic evaluation

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Full Research Paper

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Keywords:
A_4B_2-hexaphyrin; A_3B-porphyrin; *N*-tosylimine; $Cu(OTf)_2$ catalysis; HRESI–TOF analysis

Beilstein J. Org. Chem. **2023,** *19,* 1832–1840.
https://doi.org/10.3762/bjoc.19.135

Received: 20 August 2023
Accepted: 23 November 2023
Published: 06 December 2023

Associate Editor: N. Yoshikai

Abstract

A substituent-dependent construction of novel A_3B-porphyrins along with A_4B_2-hexaphyrins was realized by the reactions of *N*-tosylimines and *meso*-aryl-substituted tripyrranes in the presence of $Cu(OTf)_2$ as the catalyst. The reaction mechanism of the presented method was studied on model reactions by electrospray-ionization time-of-flight (HRESI–TOF) mass spectral analysis in a timely manner. The analytical results indicated that the observed azafulvene-ended di- and tripyrrolic intermediates are responsible for the formation of porphyrinogen and hexaphyrinogen forms.

Introduction

Porphyrins and expanded porphyrins have found widespread applications in supramolecular chemistry [1-4]. Expanded porphyrins are utilized as building blocks in the fields of near-infrared (NIR) dyes [5], nonlinear optical (NLO) materials [2], and photosensitizers in photodynamic therapy [1], however, their synthesis is still a challenge for chemists. Hexaphyrins are one of the most investigated structures among expanded porphyrins owing to their structural stability, flexibility, or complexing ability with transition metals [6-12]. *meso*-Aryl-substituted dipyrromethanes or tripyrranes are the most commonly used starting materials in hexaphyrin syntheses [13-16]. Osuka et al. made significant contributions to the selective synthesis of expanded porphyrins and their chemistry with regard to their aromaticity and coordination properties. They used *meso*-aryl-substituted dipyrromethanes and aldehydes in the synthesis of A_3B_3-type hexaphyrins [13] and 5,10-diaryl-substituted tripyrranes in A_4B_2-hexaphyrin synthesis [6,17-20]. Similarly, the syntheses of A_mB_n-type hexaphyrins, octaphyrins, or higher expanded porphyrins were handled by improved methods in recent years with the use of tripyrranes or bilanes and aldehydes [7,14,21-25].

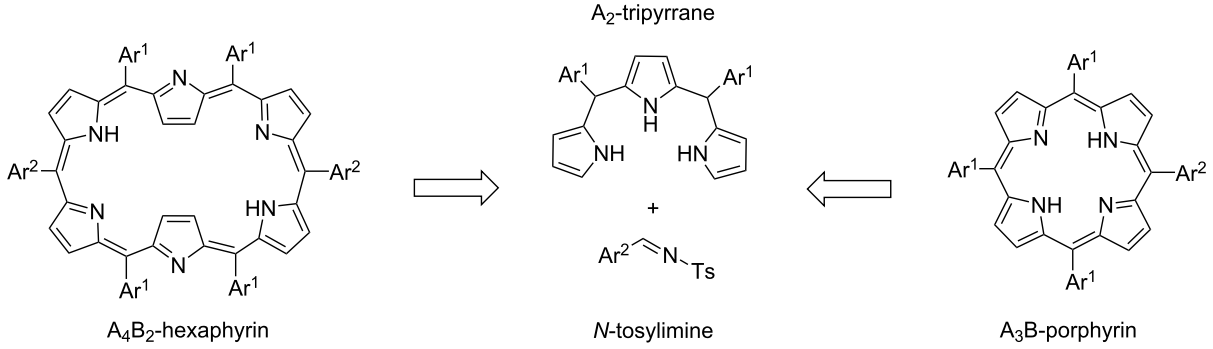
In our previous studies, we used *N*-tosylimines throughout the syntheses of several porphyrinic compounds which emphasized

the usability of *N*-tosylimines with dipyrromethanes, tripyrranes, or bilanes instead of aldehydes in the synthesis of porphyrins and contracted/expanded porphyrins [26-28]. It was shown that the reaction of *meso*-pentafluorophenyl-substituted *N*-tosylimine and 5,10-bis(pentafluorophenyl)tripyrromethane formed A_6-hexaphyrin as the main product along with the inevitable formation of side products, A_4-porphyrin and higher expanded porphyrins [28]. *meso*-Phenyloligopyrroles having electron-rich substituents at the 2-, 4-, or 6-positions were screened in the literature. To the best of our knowledge, hexaphyrin synthesis from the least substituted aryls appears to be not much studied. In the following study, we focused on the use of less hindered variety of precursors in hexaphyrin and porphyrin synthesis via the $Cu(OTf)_2$-catalyzed reaction of tripyrrane and tosylimine according to the retrosynthetic method given in Scheme 1. Here, we present the substituent-dependent selective construction of A_4B_2-hexaphyrins and A_3B-porphyrins with good yields without the formation of expanded counterparts. Beyond the synthesis, for better understanding of the product formation, mass spectral analyses of model reactions were investigated by time-dependent electrospray-ionization time-of-flight (HRESI–TOF) technique.

Results and Discussion

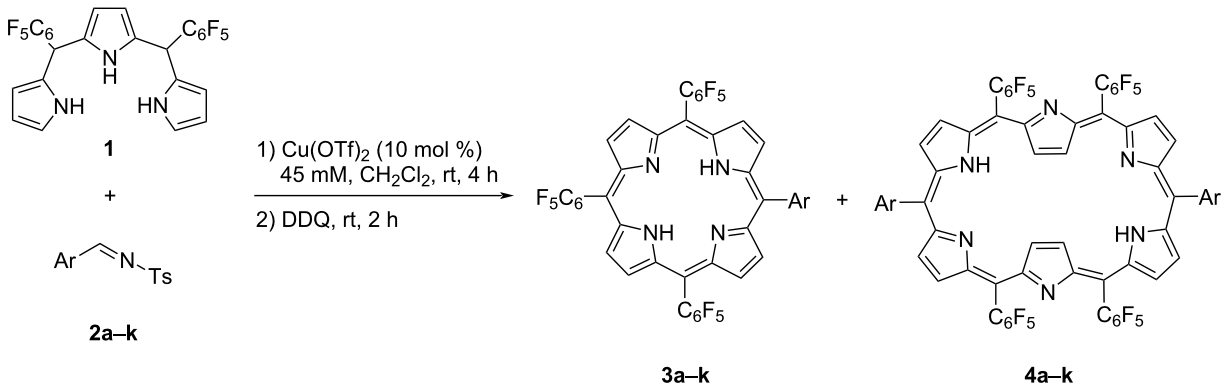
Reactions of *meso*-pentafluorophenyl-substituted A_2-tripyrrane **1** and *N*-tosylimines **2** were performed in the presence of $Cu(OTf)_2$ (Table 1). Initially, the unsubstituted phenyl-bearing *N*-tosylimine **2a** was reacted with tripyrrane **1** in CH_2Cl_2 under previously reported conditions [28], however, the desired hexaphyrin could not been isolated. Under these conditions, only product **3a**, which is defined as A_3B-type porphyrin was isolated with 15% yield (Table 1, entry 1). Then, we run the reactions of A_2-tripyrrane **1** with mesityl-containing tosylimine **2b** and 2,6-dichlorobenzylidene-substituted substrate **2c**. The desired A_4B_2-hexaphyrins **4b** and **4c** were obtained in 17% and 16% yield, respectively (Table 1, entries 2 and 3). Next, to elucidate the role of substituents present in the aromatic part of the *N*-tosylimines, the monohalogenated *N*-tosylimines **2d**–**f** and *N*-tosylimine **2g** with a strongly electron-withdrawing CF_3 substituent in the 4-position were subjected to the reaction with tripyrrane **1**. These *para*-substituted *N*-tosylimines provided the A_4B_2-hexaphyrins **4d**–**g** (Table 1, entries 4–7), with the A_4B_2-hexaphyrin **4d** isolated with 18% yield. The products **4e**–**g** were obtained in 7–10% yield and their formation was corroborated by HRMS spectral analysis (Figures S64–S66 in Supporting Information File 1). In these reactions, the A_3B-porphyrins concomitantly formed in yields between 9–17%. When *p*-methoxy- and *p*-hydroxy-substituted *N*-tosylimines **2h** and **2i** were used in this reaction, substrate **2h** gave only the A_3B-porphyrin while the imine **2i** did not form any product (Table 1, entries 8 and 9). To further evaluate the scope of the reaction, heteroaryl-bearing tosylimines were also tested. The thiophene-substituted tosylimine **2j** gave hexaphyrin **4j** in 17% yield and porphyrin **3j** in 10% yield, whereas the indole-bearing tosylimine gave only A_3B-porphyrins but no A_4B_2-hexaphyrin (Table 1, entries 10 and 11). Signals of trace amounts of A_2B_2-type porphyrins were detected in the mass spectra of some of the products. ^{1}H NMR analysis of the synthesized hexaphyrins proved that the spectra were in consistence with [26]hexaphyrin aromaticity [29]. Several other metal triflates such as $Zn(OTf)_2$, $Gd(OTf)_3$, and $Yb(OTf)_3$ were also tested as catalysts in the reaction of 4-fluorophenyl-substituted tosylimine **2d** and tripyrrane **1** and lower yields of the A_4B_2-hexaphyrins and A_3B-porphyrins were obtained compared to the reaction catalyzed by $Cu(OTf)_2$ (Table S2 in Supporting Information File 1).

The synthesis of A_3B-porphyrins is effortful and only few studies have been reported involving the use of A_3-bilanes [30,31] or dipyrromethane–dicarbinols [32], the modification of A_4-porphyrins [33], or the reaction of pyrrole with different aldehydes [34]. In the present work, the applied synthetic method provided the A_3B-porphyrins in a single-step reaction from bispentafluorophenyl-substituted tripyrrane **1** and variously substituted *N*-tosylimines **2** along with the targeted



Scheme 1: Retrosynthetic method for A_4B_2-hexaphyrin and A_3B-porphyrin synthesis.

Table 1: Synthesis of A_3B-porphyrins and A_4B_2-hexaphyrins.



Entry	*N*-Tosylimine **2**	Ar	Yield[a] (%) **3a–h,j,k**	Yield[a] (%) **4b–g,j**
1	**a**	C_6H_5	15	–
2	**b**	2,4,6-$(CH_3)_3C_6H_2$	17	17
3	**c**	2,6-Cl_2-C_6H_3	13	16
4	**d**	4-FC_6H_4	17	18
5	**e**	4-ClC_6H_4	9	7[b]
6	**f**	4-BrC_6H_4	16	10[b]
7	**g**	4-$CF_3C_6H_4$	13	10[b]
8	**h**	4-$(OCH_3)C_6H_4$	22	–
9	**i**	4-$(OH)C_6H_4$	–	–
10	**j**	thiophen-2-yl	10	17
11	**k**	indol-3-yl	22	–

[a]Isolated yields after flash column chromatography; [b]identified by HRMS analysis, NMR spectra could not be recorded due to low solubility.

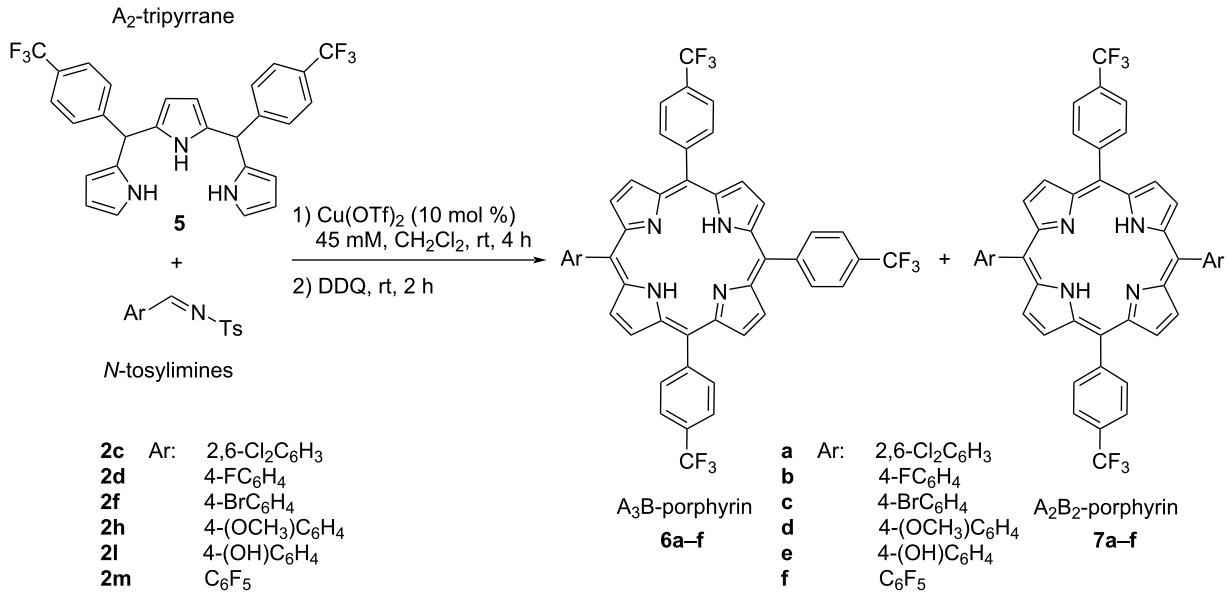
[26]hexaphyrins. Additionally, each reaction was also run with aldehydes to compare the effectiveness of *N*-tosylimines and aldehydes on this system. In most cases, the yields were lower than those in the reactions with *N*-tosylimines for both A_4B_2-hexaphyrins and A_3B-porphyrins (Table S1 in Supporting Information File 1).

Until now, we have investigated the effect of substituents present in the aryl substituent of the *N*-tosylimines on the product formation. At this point, we chose 5,10-bis(4-trifluoromethylphenyl)tripyrromethane (**5**) as a representative example to investigate the role of the tripyrrane on the reaction. A series of reactions of tripyrrane **5** with tosylimines **2c**,**d**,**f**,**h**,**l**,**m** were performed. In this case, tripyrrane **5** principally formed A_3B-porphyrins (Table 2, entries 1–6) and in some cases A_2B_2-porphyrins, but disfavored the formation of A_4B_2-hexaphyrins. As outlined in Table 2, the reactions of *N*-tosylimines **2d**,**f**,**l**,**m** with tripyrrane **5** resulted in the formation of A_3B-porphyrins **6b**,**c**,**e**,**f** in yields ranging between 12–28%, respectively, where the corresponding A_2B_2-porphyrins were formed in trace amounts (Table 2, entries 2, 3, 5, and 6). A_3B-porphyrin **6a** was isolated as the sole product with 13% yield (Table 2, entry 1). In the case of *N*-tosylimine **2h**, the reaction gave A_3B-porphyrin **6d** and *trans*-A_2B_2-porphyrin **7d** with 21% and 10% yield, respectively (Table 2, entry 4).

In this work, the role of substituents on tripyrranes and *N*-tosylimines on product formation has been shown and the synthesis of A_3B-porphyrins and a variety of A_4B_2-hexaphyrins has been achieved. The presence of the bulky electron-withdrawing pentafluorophenyl group in tripyrranes controls the formation of A_4B_2-hexaphyrins as mentioned by Osuka and Suzuki [13], besides the formation of A_3B-porphyrins. On the other hand, electron-withdrawing but less bulky (4-trifluoromethylphenyl) groups on tripyrrane **5** led to predominant formation of the A_3B-porphyrin even when it was reacted with mono-, di-, or penta-substituted aryl *N*-tosylimino substrates (Table 2).

To elucidate the product diversity and to follow the progress of the reaction, a series of mass spectral analysis of the reaction mixture of 4-fluorophenyl-substituted *N*-tosylimine **2d** and

Table 2: Synthesis of A_mB_n-type porphyrins with electron-deficient tripyrrane **5**.



Entry	*N*-Tosylimine	A_3B-porphyrin	Yield[a] (%)	A_2B_2-porphyrin	Yield[a] (%)
1	**2c**	**6a**	13	**7a**	–
2	**2d**	**6b**	28	**7b**	trace[b]
3	**2f**	**6c**	15	**7c**	trace[b]
4	**2h**	**6d**	21	**7d**	10
5	**2l**	**6e**	12	**7e**	trace[b]
6	**2m**	**6f**	12	**7f**	trace[b]

[a]Isolated yields after flash column chromatography; [b]identified by HRMS analysis.

tripyrrane **1** has been conducted at 0 °C. Samples were taken from the reaction medium at certain time intervals within 2 hours and examined by ESI LC–MS.

Throughout the high-resolution electrospray-ionization time-of-flight (HRESI–TOF) mass analysis of the reaction mixture at 0 °C, the following peaks were observed: *m/z* = 246.0366 ($[M + H]^+$ calcd for $C_{11}H_5F_5N$, 246.0337), *m/z* = 857.1468 ($[M + Na]^+$ calcd for $C_{40}H_{25}F_{11}N_4O_2SNa$, 857.1415), *m/z* = 664.1292 ($[M + H]^+$ calcd for $C_{33}H_{17}F_{11}N_3$, 664.1241), *m/z* = 1134.2119 ($[M + Na]^+$ calcd for $C_{54}H_{37}F_{12}N_5O_4S_2Na$, 1134.1988), *m/z* = 963.1694 ($[M + Na]^+$ calcd for $C_{47}H_{28}F_{12}N_4O_2SNa$, 963.1634), *m/z* = 792.1343 ($[M + Na]^+$ calcd for $C_{40}H_{19}F_{12}N_3Na$, 792.1280), corresponding to the intermediates **I**–**VI**, respectively (Figure 1, Figures S46 and S47 in Supporting Information File 1). At the very first two minutes of the reaction run at 0 °C no mass signals attributable to reaction intermediates were observed but only signals of the starting materials **1** and **2d** both in the negative and positive ion mode. After two minutes, tripyrrane sulfonamide **II** and azafulvene **I** mass peaks were observed. Later on, tripyrrolic intermediates **III** and **VI** predominated and the mass peak of **IV** was observed with poor intensity in the spectra (Figure 1 and Figure S47 in Supporting Information File 1).

In our previous works, we have shown that the reaction of pyrrole with *N*-tosylimines leads to pyrrole sulfonamides as the main products [35]. In another work, in the synthesis of dipyrromethane structures, we have proven the formation of azafulvene intermediates by $Cu(OTf)_2$-appended elimination of sulfonamide groups from pyrrolic sulfonamides [36]. Here in this work, during the reaction at 0 °C, intermediates **I**–**VI** were detected (Figure 1). The primary intermediates **II** and **IV** are formed by the addition of tripyrrane **1** to tosylimine **2d**. Further elimination of *N*-tosyl group(s) from these intermediates gives azafulvene-ended secondary intermediates **III**, **V**, and **VI**. The observed intermediates **I**–**VI** having sulfonamide or azafulvene ends are in accordance with our previous findings [26,35,36]. In addition, the observation of azafulvene **I** could be attributed to the fragmentation of tripyrrane **1**, intermediates **II** or **III** as pro-

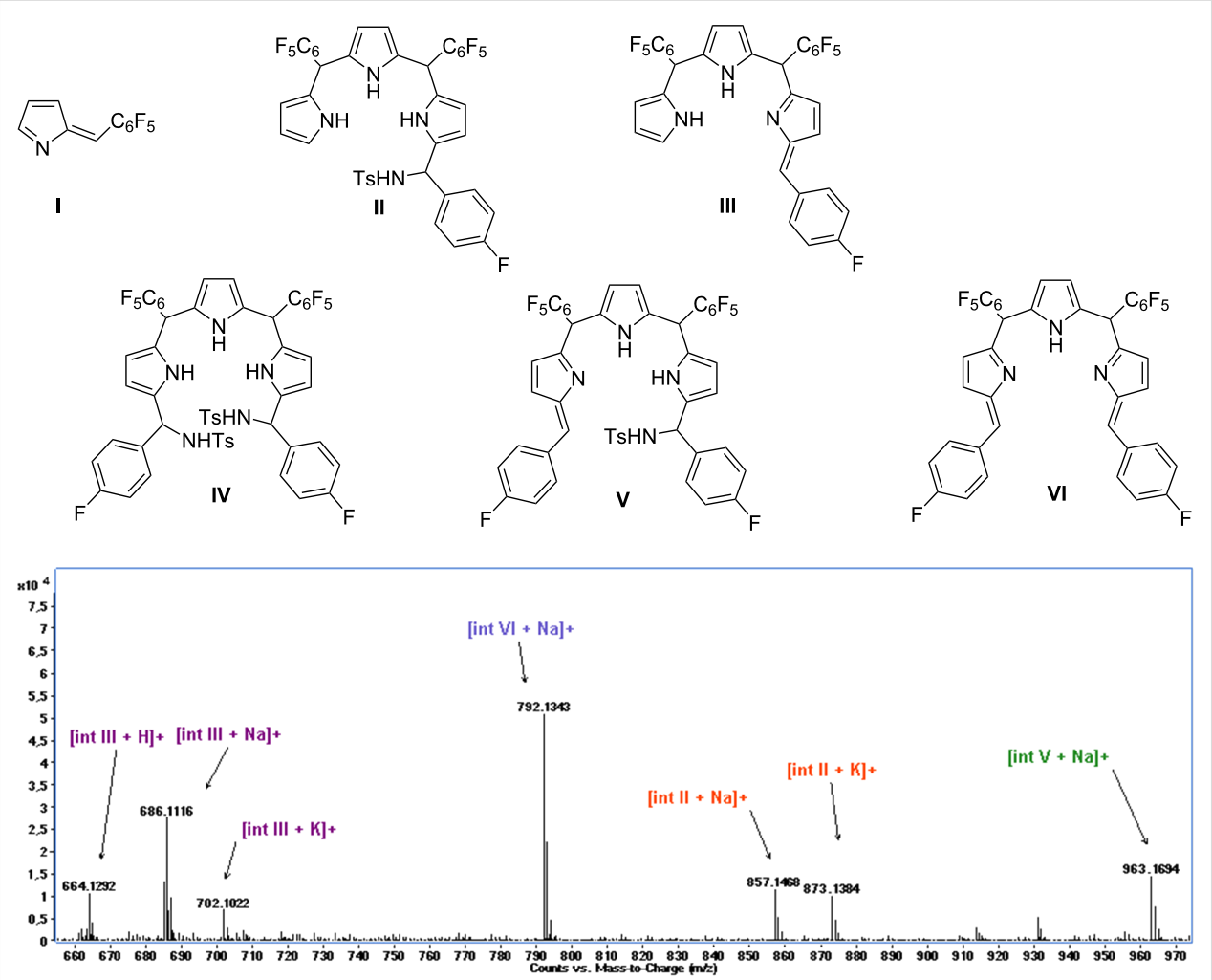
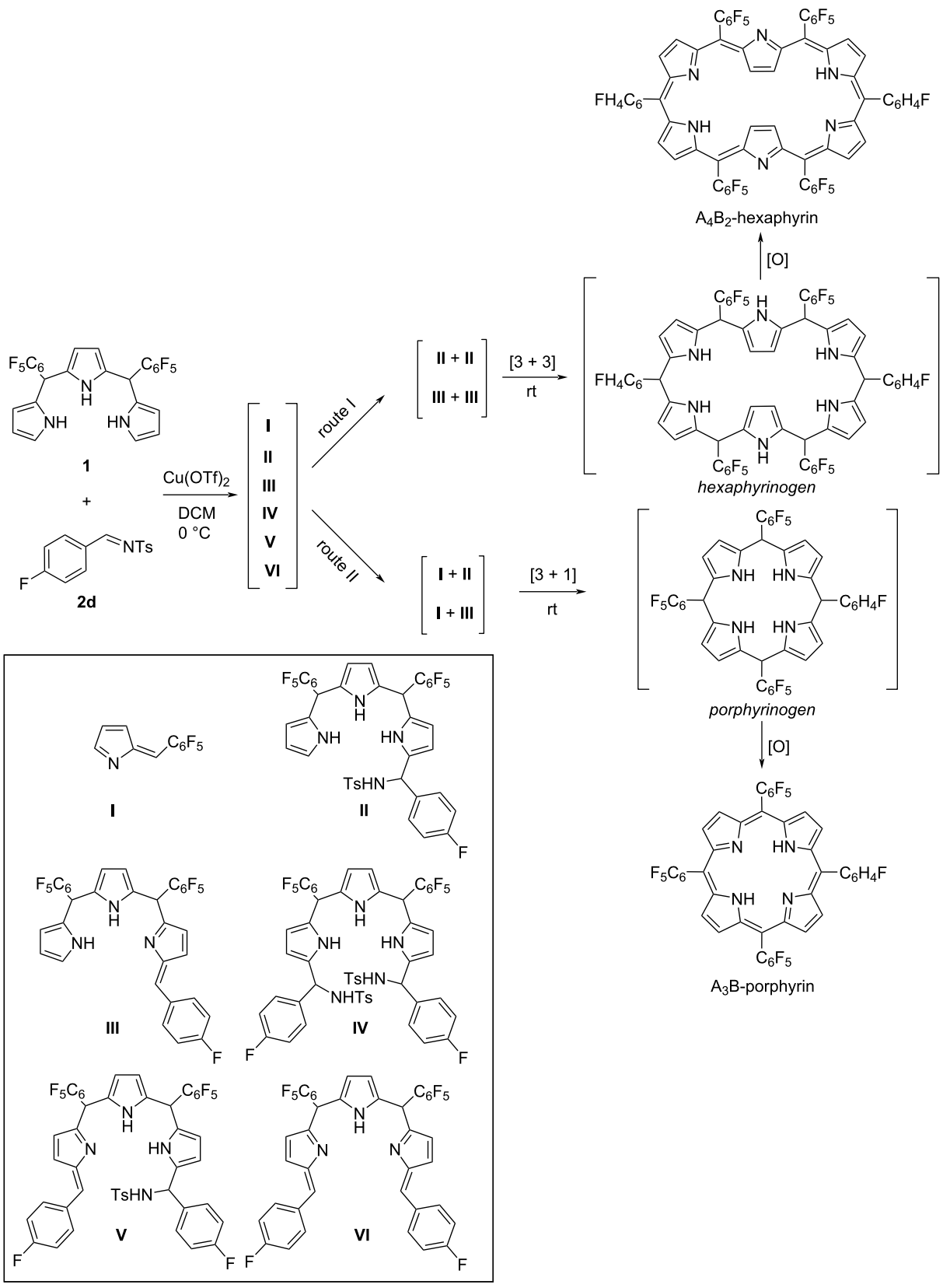


Figure 1: Mass spectrum of the reaction mixture of **1** and **2d** at 30 min at 0 °C with assigned intermediates (positive ion mode).

posed in Figure S75 in Supporting Information File 1. These structures (**I**–**VI**) could be said to be responsible for the selective formation of porphyrin and hexaphyrin products. When the temperature was increased to rt, porphyrinogen forms of A_3B-porphyrin and A_4B_2-hexapyrin were predominately observed (Figure S48 in Supporting Information File 1).

According to high-resolution electrospray-ionization time-of-flight (HRESI–TOF) analysis, at the beginning of the reaction, mass peaks of intermediates **II** and **IV** arose as a result of tripyrrane **1** addition to *N*-tosylimine **2d**. Further eliminations of sulfonamide groups from **II** and **IV** formed the intermediates **III**, **V** and **VI**. A plausible reaction pathway for the formation of A_4B_2-hexaphyrin and A_3B-porphyrin was suggested taking into account the combination of these detected intermediates (Scheme 2). In route I, [3 + 3] reactions of intermediates **II** or **III**, at rt form hexaphyrinogen and the subsequent oxidation gives A_4B_2-hexaphyrin. Similarly, [3 + 1] reactions of intermediates **I** and **II** or **I** and **III** provide the formation of porphyrinogen and their oxidation gives A_3B-porphyrin as indicated in route II. The presence of starting material **1** in the reaction medium can provide the formation of A_4B_2-hexaphyrin through the reaction with the intermediates **IV**, **V**, or **VI**. These routes are considered as less likely to happen where intermediates **II** and **III** dominate the reaction medium according to the mass analysis as stated before. For this reason, in Scheme 2 below, more probable cyclization pathways have been displayed.

A similar LC–MS analysis was made for the reaction of tripyrrane **5** and 4-methoxyphenyl-substituted tosylimine **2h** at 0 °C which mainly formed A_3B-porphyrins. This time, the primary tosylated intermediates were not detected, instead *N*-tosyl eliminated azafulvene-ended secondary intermediates **VII**–**XII** (Figure 2) were observed, respectively, at m/z = 224.0627 ($[M + H]^+$ calcd for $C_{12}H_9F_3N$, 224.0682), m/z = 445.1150



Scheme 2: A suggested reaction pathway for the formation of A_4B_2-hexaphyrins and A_3B-porphyrins.

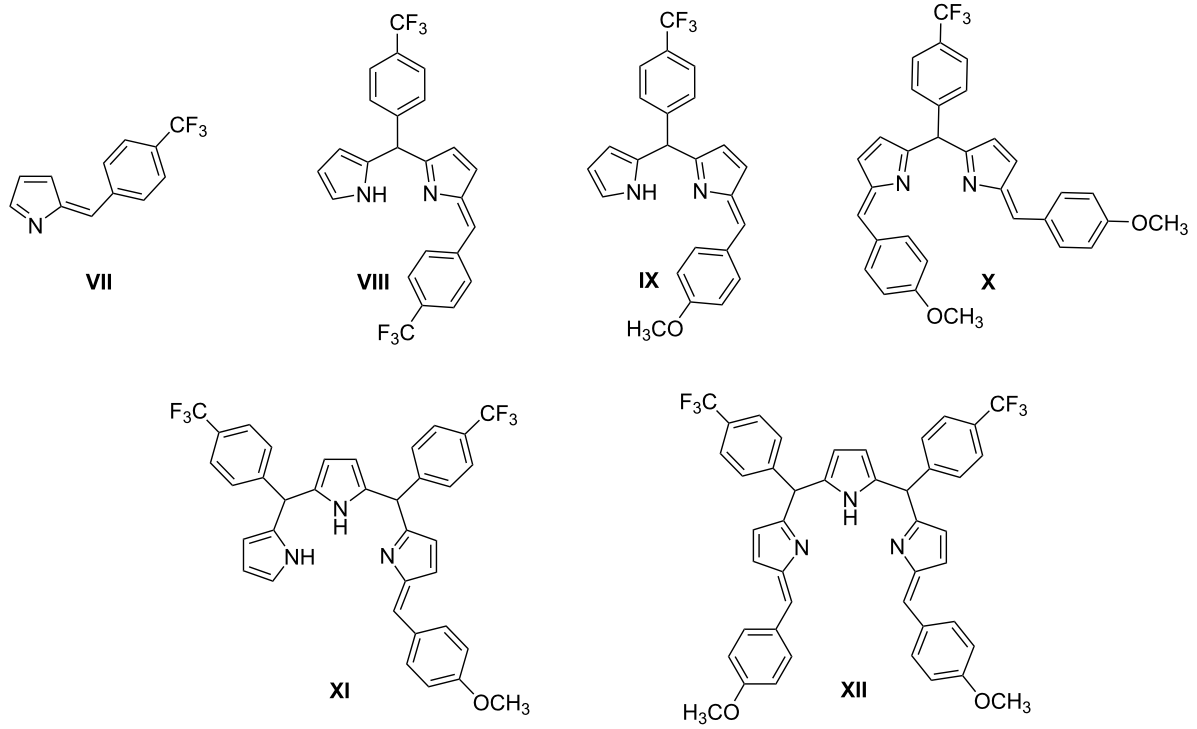


Figure 2: Intermediates in the reaction mixture of **5** and **2h** at 30 min at 0 °C.

([M − H]$^-$ calcd for $C_{24}H_{15}F_6N_2$, 445.1145), *m*/*z* = 409.1411 ([M + H]$^+$ calcd for $C_{24}H_{20}F_3N_2O$, 409.1522), *m*/*z* = 527.1795 ([M + H]$^+$ calcd for $C_{32}H_{26}F_3N_2O_2$, 527.1941), *m*/*z* = 630.1985 ([M − H]$^-$ calcd for $C_{36}H_{26}F_6N_3O$, 630.1986), and *m*/*z* = 750.2364 ([M + H]$^+$ calcd for $C_{44}H_{34}F_6N_3O_2$, 750.2550) (Figure S49 in Supporting Information File 1). Although the positive ion peaks of tripyrrolic intermediates **XI** and **XII** were observed, any hexaphyrin products did form from this set of reactions. Yet, A_3B-porphyrins were clearly and selectively formed over A_2B_2-porphyrins, even the positive ion peaks of dipyrrolic intermediates **VIII**, **IX**, and **X** have been observed (Figure S49 in Supporting Information File 1). A reaction pathway for the predominant formation of A_3B-porphyrin considering the reaction of tripyrrane **5** and tosylimine **2h** was also proposed and is given in Figure S50 of Supporting Information File 1, in which only the azafulvene-ended intermediates **VII**–**XII** were detected.

Conclusion

In conclusion, a set of A_4B_2-hexaphyrins and A_3B-porphyrins were selectively synthesized through the $Cu(OTf)_2$-catalyzed reactions of *N*-tosylimines and tripyrranes under mild reaction conditions. With these reactions, it has been shown that the C_6F_5 group led to the formation of hexaphyrin and porphyrins as well as the monosubstituted aryl-bearing *N*-tosylimines, but a 4-$(CF_3)C_6H_4$ group led only to the formation of porphyrin compounds.

A mechanistic perspective for the formation of porphyrinic products was acquired via a set of high-resolution mass analyses of selected model reactions. The results indicated that azafulvene-ended tripyrrolic intermediates **III**, **V**, and **VI** or sulfonamide-ended intermediates **II** and **IV** along with monopyrrolic fragment **I** derives the formation of porphyrins and hexaphyrins. This study offers an insight to the design of A_4B_2-hexaphyrins and A_3B-porphyrins by utilizing the substituents on tripyrranes and *N*-tosylimines.

Experimental

General method: All reagents and solvents were purchased from Sigma-Aldrich, Fisher Scientific, or Acros Organics and were used without further purification. ^{1}H NMR (400 MHz), ^{13}C NMR (100 MHz), and ^{19}F NMR (376 MHz) spectra were recorded on a Bruker 400, Ultra Shield high-performance digital FT-NMR spectrometer. Data for ^{1}H NMR, ^{13}C NMR, and ^{19}F NMR are reported as follows: chemical shift (δ, ppm), multiplicity (s = singlet, d = doublet, t = triplet, m = multiplet, q= quartet, bs = broad singlet, dd = doublet of doublets, td = triplet of doublets, qd = quartet of doublets), coupling constant, number of atoms. UV–vis absorption spectra were recorded on

a Mapada Instruments UV3100PC spectrophotometer. Mass spectra were recorded on an Agilent 1200/6210 high-resolution mass time-of-flight (TOF) LC–MS spectrometer. Reactions were followed by thin-layer chromatography (TLC, Kieselgel 60, F254, Merck) with visualization under UV light. Products were purified by silica gel flash column chromatography (0.05–0.63 mm, 230–400 mesh ASTM, E.Merck). *N*-Tosylimines **2a**–**m** and 5,10-bis(pentafluorophenyl)tripyrromethane (**1**) were synthesized according to the previously reported literature procedures [35,37].

Synthesis of porphyrin compounds **3a–h**,**j**,**k** and **4b–g**,**j**

N-Tosylimine **2** (0.090 mmol) and $Cu(OTf)_2$ (0.0090 mmol) were dissolved in CH_2Cl_2 (0.5 mL) and stirred at room temperature for 30 minutes under N_2 atmosphere. To this mixture was added a solution of 5,10-bis(pentafluorophenyl)tripyrromethane (**1**, 0.090 mmol) in CH_2Cl_2 (1.5 mL) and the mixture was stirred at rt for 4 h. Afterwards, DDQ (0.180 mmol) was added to this solution and stirred for another 2 h. The resulting solution was eluted through a short silica gel column with EtOAc and the solvent was removed under reduced pressure. The residue was purified by silica gel column chromatography (EtOAc/hexane 1:50) or preparative thin-layer chromatography on silica gel (Silica gel 60, F254, Merck) where applicable to obtain A_3B-porphyrins and A_4B_2-hexaphyrins. Yields of porphyrins **3a**–**k** were between 9–22% and the yields of hexaphyrins **4b**–**g**,**j** were between 7–18%.

Synthesis of tripyrrane **5**

5,10-Bis(4-trifluoromethylphenyl)tripyrromethane (**5**) was obtained as side product of dipyrromethane synthesis by the condensation of pyrrole and 4-(trifluoromethyl)benzaldehyde. A typical procedure involves 4-(trifluoromethyl)benzaldehyde (28.7 mmol) and pyrrole (143.6 mmol) in 3 mL:197 mL HCl/H_2O. The resulting mixture was controlled by TLC and after 4 h, the mixture was extracted with EtOAc (50 mL × 3). The reaction crude was then purified by flash column chromatography (EtOAc/hexane 1:10) to give compound **5** in 20% yield.

Synthesis of porphyrin compounds **6a–f** and **7d**

N-Tosylimine **2** (0.097 mmol) and $Cu(OTf)_2$ (0.0097 mmol) were dissolved in CH_2Cl_2 (0.5 mL) and stirred at room temperature for 30 min under N_2 atmosphere. To this mixture was then added a solution of 5,10-bis(4-trifluoromethylphenyl)tripyrromethane (**5**, 0.097 mmol) in CH_2Cl_2 (1.5 mL) and stirred at rt for 4 h. Afterwards, DDQ (0.195 mmol) was added to this solution and stirred for another 2 h. The resulting solution was eluted through a short silica gel column with EtOAc and the solvent was removed under reduced pressure. The residue was purified by silica gel column chromatography (EtOAc/hexane 1:50) or preparative thin-layer chromatography on silica gel (silica gel 60, F254, Merck) where applicable to obtain A_3B-porphyrins **6a–f**, and **7d** in yields between 10–28%.

Supporting Information

Supporting Information File 1

Analytical data and copies of spectra.
[https://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-19-135-S1.pdf]

Acknowledgements

The presented work is a part of the Ph.D. thesis entitled “Synthesis of Porphyrins and Expanded Porphyrins from Oligopyrrolic Compounds and Investigatıon of Their Photophysical Properties” written by Seda Cinar, Hacettepe University, Graduate School of Science and Engineering, Beytepe Campus, 06800, Ankara, Turkey.

Funding

SC thanks The Scientific and Technological Research Council of Turkey (TUBITAK) for doctoral scholarship (2211-C Domestic Ph.D. Scholarship Programme for Priority Areas).

Author Contributions

S. C. investigation, experimental, writing; D. I. T. experimental, writing; C. U. investigation, writing and resources.

Conflict of Interest

The authors declare no conflict of interest.

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References

1. Sessler, J. L.; Miller, R. A. *Biochem. Pharmacol.* **2000,** *59,* 733–739. doi:10.1016/s0006-2952(99)00314-7
2. Rath, H.; Sankar, J.; PrabhuRaja, V.; Chandrashekar, T. K.; Nag, A.; Goswami, D. *J. Am. Chem. Soc.* **2005,** *127,* 11608–11609. doi:10.1021/ja0537575
3. Young, S. W.; Qing, F.; Harriman, A.; Sessler, J. L.; Dow, W. C.; Mody, T. D.; Hemmi, G. W.; Hao, Y.; Miller, R. A. *Proc. Natl. Acad. Sci. U. S. A.* **1996,** *93,* 6610–6615. doi:10.1073/pnas.93.13.6610
4. Kostas, I. D.; Coutsolelos, A. G.; Charalambidis, G.; Skondra, A. *Tetrahedron Lett.* **2007,** *48,* 6688–6691. doi:10.1016/j.tetlet.2007.07.141

5. Wu, D.; Descalzo, A. B.; Weik, F.; Emmerling, F.; Shen, Z.; You, X.-Z.; Rurack, K. *Angew. Chem., Int. Ed.* **2008,** *47,* 193–197. doi:10.1002/anie.200702854
6. Suzuki, M.; Osuka, A. *Chem. – Eur. J.* **2007,** *13,* 196–202. doi:10.1002/chem.200601147
7. Misra, R.; Kumar, R.; Chandrashekar, T. K.; Joshi, B. S. *J. Org. Chem.* **2007,** *72,* 1153–1160. doi:10.1021/jo061861e
8. Jasat, A.; Dolphin, D. *Chem. Rev.* **1997,** *97,* 2267–2340. doi:10.1021/cr950078b
9. Shin, J.-Y.; Kim, K. S.; Yoon, M.-C.; Lim, J. M.; Yoon, Z. S.; Osuka, A.; Kim, D. *Chem. Soc. Rev.* **2010,** *39,* 2751–2767. doi:10.1039/b925417j
10. Saito, S.; Osuka, A. *Angew. Chem., Int. Ed.* **2011,** *50,* 4342–4373. doi:10.1002/anie.201003909
11. Ishida, S.-i.; Soya, T.; Osuka, A. *Angew. Chem., Int. Ed.* **2018,** *57,* 13640–13643. doi:10.1002/anie.201808513
12. Kang, S.; Hayashi, H.; Umeyama, T.; Matano, Y.; Tkachenko, N. V.; Lemmetyinen, H.; Imahori, H. *Chem. – Asian J.* **2008,** *3,* 2065–2074. doi:10.1002/asia.200800229
13. Suzuki, M.; Osuka, A. *Org. Lett.* **2003,** *5,* 3943–3946. doi:10.1021/ol035650x
14. Kamimura, Y.; Shimizu, S.; Osuka, A. *Chem. – Eur. J.* **2007,** *13,* 1620–1628. doi:10.1002/chem.200601304
15. Taniguchi, R.; Shimizu, S.; Suzuki, M.; Shin, J.-Y.; Furuta, H.; Osuka, A. *Tetrahedron Lett.* **2003,** *44,* 2505–2507. doi:10.1016/s0040-4039(03)00328-9
16. Tanaka, Y.; Shin, J.-Y.; Osuka, A. *Eur. J. Org. Chem.* **2008,** 1341–1349. doi:10.1002/ejoc.200701132
17. Suzuki, M.; Osuka, A. *Chem. Commun.* **2005,** 3685–3687. doi:10.1039/b506586k
18. Koide, T.; Kashiwazaki, G.; Suzuki, M.; Furukawa, K.; Yoon, M.-C.; Cho, S.; Kim, D.; Osuka, A. *Angew. Chem., Int. Ed.* **2008,** *47,* 9661–9665. doi:10.1002/anie.200804570
19. Naoda, K.; Mori, H.; Osuka, A. *Chem. Lett.* **2013,** *42,* 22–24. doi:10.1246/cl.2013.22
20. Naoda, K.; Mori, H.; Oh, J.; Park, K. H.; Kim, D.; Osuka, A. *J. Org. Chem.* **2015,** *80,* 11726–11733. doi:10.1021/acs.joc.5b01348
21. Mori, H.; Aratani, N.; Osuka, A. *Chem. – Asian J.* **2012,** *7,* 1340–1346. doi:10.1002/asia.201100919
22. Naoda, K.; Mori, H.; Aratani, N.; Lee, B. S.; Kim, D.; Osuka, A. *Angew. Chem., Int. Ed.* **2012,** *51,* 9856–9859. doi:10.1002/anie.201204446
23. Sessler, J. L.; Seidel, D.; Bucher, C.; Lynch, V. *Tetrahedron* **2001,** *57,* 3743–3752. doi:10.1016/s0040-4020(01)00243-5
24. Saito, S.; Osuka, A. *Chem. – Eur. J.* **2006,** *12,* 9095–9102. doi:10.1002/chem.200600671
25. Tanaka, T.; Osuka, A. *Chem. Rev.* **2017,** *117,* 2584–2640. doi:10.1021/acs.chemrev.6b00371
26. Temelli, B.; Unaleroglu, C. *Tetrahedron* **2009,** *65,* 2043–2050. doi:10.1016/j.tet.2009.01.009
27. Aydin, G.; Temelli, B.; Unaleroglu, C. *Eur. J. Org. Chem.* **2015,** 7583–7593. doi:10.1002/ejoc.201501062
28. Cinar, S.; Temelli, B.; Unaleroglu, C. *Tetrahedron Lett.* **2014,** *55,* 544–547. doi:10.1016/j.tetlet.2013.11.101
29. Neves, M. G. P. M. S.; Martins, R. M.; Tomé, A. C.; Silvestre, A. J. D.; Silva, A. M. S.; Félix, V.; Cavaleiro, J. A. S.; Drew, M. G. B. *Chem. Commun.* **1999,** 385–386. doi:10.1039/a808952c
30. Hatay, I.; Su, B.; Méndez, M. A.; Corminboeuf, C.; Khoury, T.; Gros, C. P.; Bourdillon, M.; Meyer, M.; Barbe, J.-M.; Ersoz, M.; Záliš, S.; Samec, Z.; Girault, H. H. *J. Am. Chem. Soc.* **2010,** *132,* 13733–13741. doi:10.1021/ja103460p
31. Nowak-Król, A.; Plamont, R.; Canard, G.; Edzang, J. A.; Gryko, D. T.; Balaban, T. S. *Chem. – Eur. J.* **2015,** *21,* 1488–1498. doi:10.1002/chem.201403677
32. Rao, P. D.; Dhanalekshmi, S.; Littler, B. J.; Lindsey, J. S. *J. Org. Chem.* **2000,** *65,* 7323–7344. doi:10.1021/jo000882k
33. Presolski, S. I.; van der Weegen, R.; Wiesfeld, J. J.; Meijer, E. W. *Org. Lett.* **2014,** *16,* 1864–1867. doi:10.1021/ol500182z
34. Little, R. G. *J. Heterocycl. Chem.* **1981,** *18,* 129–133. doi:10.1002/jhet.5570180126
35. Temelli, B.; Unaleroglu, C. *Tetrahedron Lett.* **2005,** *46,* 7941–7943. doi:10.1016/j.tetlet.2005.09.090
36. Temelli, B.; Unaleroglu, C. *Tetrahedron* **2006,** *62,* 10130–10135. doi:10.1016/j.tet.2006.08.047
37. Ka, J.-W.; Lee, C.-H. *Tetrahedron Lett.* **2000,** *41,* 4609–4613. doi:10.1016/s0040-4039(00)00672-9

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