Rim-Differentiated C₅-Symmetric Tiara-Pillar[5]arenes

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Supporting Information

ABSTRACT: The synthesis of “rim-differentiated” C₅-symmetric pillar[5]arenes, whose two rims are decorated with different chemical functionalities, has remained a challenging task. This is due to the inherent statistical nature of the cyclization of 1,4-disubstituted alkoxybenzenes with different substituents, which leads to four constitutional isomers with only 1/16th being rim-differentiated. Herein, we report a “preoriented” synthetic protocol based on FeCl₃-catalyzed cyclization of asymmetrically substituted 2,5-dialkoxybenzyl alcohols. This yields an unprecedented 55% selectivity of the C₅-symmetric tiara-like pillar[5]arene isomer among four constitutional isomers. Based on this new method, a series of functionalizaliable tiara-pillar[5]arene derivatives with C₅-symmetry was successfully synthesized, isolated, and fully characterized in the solid state.

Since being introduced¹ almost a decade ago, pillararenes,² in particular the cyclopentameric pillar[5]arenes (P[5]s), have received rapidly growing attention of the macrocyclic,³ supramolecular,⁴ and mechanostereochemistry⁵ communities. In addition to their straightforward syntheses⁶ and promiscuous guest−host properties,⁷ another reason for the popularity of P[5]s is their versatility in functionalization⁸ compared to other semimalcyclic systems, such as cycloexetrins,⁹ crown ethers,¹⁰ cucurbiturils,¹¹ and calixarenes.¹² The five hydroquinone rings in the P[5] scaffold offer 10 phenolic sites for further derivatization, either before the P[5] macrocycle formation or through postsynthetic modification approaches.

Among all synthetically accessible functionalization patterns, the most symmetric per-functionalized¹³ P[5]s, are the easiest synthetic targets. The syntheses of P[5]s with lower symmetry, such as mono-,¹⁴ and (A1/A2)-disubstituted¹⁵ ones, can be still relatively easily achieved through cocrystallization of different types of 1,4-dialkoxybenzene monomers, or partial demethylation of the 1,4-dimethoxybenzene moieties in the P[5] scaffold. In contrast, selective syntheses of oligo-substituted P[5]s, in particular the so-called “rim-differentiated” C₅-symmetric pillar[5]arenes,¹⁶ or briefly tiara-pillar[5]arenes (T-P[5]s), in which the two rims of the P[5] macrocycles are decorated differently, have remained elusive. This is due to the statistical nature of the cyclization process of 1,4-dialkoxybenzenes with different alkoxy groups, which yields the four constitutional isomers in a ratio of 5:5:5:1, with only the latter being the T-P[5]. As a result, this process typically gives rise to both low selectivity (~1/16th, thus maximally only ~6% of all P[5]s) and concomitantly even lower isolated yields.

This situation needs to be improved significantly, as indicated by both Ogoshi (ref 2b) and Stoddart (ref 8), in that novel strategies toward T-P[5]s are not only highly desirable but also required to take full advantage of the potential of this class of compounds. T-P[5]s are, for example, very appealing molecular design platforms on account of their high C₅-symmetry and their differing functionalities on either side of the macrocycles. By exploiting this unique symmetry, self-assembled micellar, vesicular, and tubular superstructures of several T-P[5]-based amphiphiles modified with hydrophilic and hydrophobic groups on opposite sides have been developed¹⁷ for potential applications, e.g. artificial ion channels.¹⁸ In addition, on account of their rim-differentiation, T-P[5]s, like many calixarenes, are ideal targets to be multivalently grafted onto various surfaces,¹⁹ such as silicon²⁰ or graphene oxide,²¹ for interface applications. However, the low-yielding synthesis is still the bottleneck for further investigation and application of this C₅-isomer. The results in this paper overcome that bottleneck.

Among the hundreds of publications on pillararenes that have appeared in the past decade, only a handful of them have addressed¹⁶,¹⁷,²⁰,²² the syntheses and applications of the T-P[5]s. Generally, penta-functionalized P[5]s can be prepared (Figure 1a) from the Lewis acid-catalyzed cyclization of asymmetrically functionalized 1,4-dialkoxybenzenes (M₅) with paraformaldehyde²³ or 1,4-dialkoxy-2,5-bis(ethoxymethyl)benzenes (M₅),²⁴ forming two key intermediates (M₅/M₅) via Friedel–Crafts alkylation/dealkylation. The subsequent oligomerization processes involving M₅ and M₅ lead to two types of isomeric dimers D₅, and D₅ depending on how the two 1,4-alkoxylated benzene rings and the methylene bridges are positioned relative to each other. The reaction pathways differentiate (see Supporting Information Scheme S5) even more after three following alkylation steps, leading to 32 different linear pentamers, which eventually form (see Supporting Information Scheme S6) four distinct P[5] macrocyclic isomers (Figure 1b) after the final cyclization steps. The theoretical ratio of these four isomers (based on permutations with p = 0.5) is 5:5:5:1, which is in very good agreement with experimental results in literature.¹⁶
Communication

As the model compound. Following the statistical synthetic protocol, we have relied on this type of statistical synthetic protocol to obtain (propargyl)₅-T-P[₅], the "synthesis of T-P[₅]. On the basis of this idea, herein we propose a strategy, which employs a monomer equipped with one hydroxymethylene handle installed at a specific position on the dialkoxylated benzene ring to orient the oligomerization process.

In our initial study, (propargyl)₅-(methyl)₅-tiara-P[₅] (or (propargyl)₅-T-P[₅]), the five methyl groups on the other rim are from now on omitted for clarity 2a (Figure 2a) was chosen as the model compound. Following the statistical synthetic protocol, the mixture of (propargyl)₅-P[₅] isomers was synthesized (see Supporting Information) from the condensation reaction of 1-methoxy-4-(prop-2-yn-1-yl)oxy-benzene with paraformaldehyde catalyzed by trifluoroacetic acid in 1,2-dichloroethane (DCE). Although the total cyclization yield of all four constitutional isomers combined reaches 78%, which is higher than the 51% reported in literature, only 7% of the resulting P-[₅] mixture is the desired (propargyl)₅-T-P[₅] 2a isomer, as determined by analytical HPLC (Figure 2b, also see Supporting Information).

For the "preoriented" synthesis, our initial studies were focused on optimizing the reaction parameters (see Table 1) for monomer 1a (see Supporting Information for synthesis). The popular BF₃·Et₂O-catalyzed cyclization conditions for P[₅] (Table 1, Entry 1) resulted in a 22% yield for all four constitutional isomers combined, in which the ratio of the T-[₅] isomer 2a accounted for 17% (see Supporting Information). Although the overall calculated yield of T-P[₅] 2a was merely 3.7%, this 17% selectivity showed an encouraging

Therefore, the yield for the C₅-symmetric T-P[₅] isomer is the lowest, accounting for only 1/16th of the total P[₅] isomers formed. So far, all literature examples involving T-P[₅]s have relied on this type of statistical synthetic protocol to obtain the desired C₅-symmetric products in barely 5–7% yield in the reaction mixtures. Isolation is then often aggravated even further by the nontrivial purification of this minor product by chromatography or HPLC.

Considering that it is the presence of both monomeric intermediates M₄ and M₅ that leads to the complicated reaction pathways and results in the isomeric mixtures, we reasoned that the exclusive use of one of the two monomers (Figure 1c), in the presence of a suitable Lewis acid, would direct toward the formation of all-syn linear pentamer (Pₛ₅) in the presence of a weak Lewis acid, resulting in T-P[₅] with high selectivity and yield.

Figure 1. (a) In the Lewis acid-catalyzed oligocyclization, the reaction of asymmetrically functionalized monomer (M₁ or M₂) with formaldehyde can form two key monomeric intermediates M₃ and M₄, which undergo further oligomerization. The alkoxy substituents (OR₁ and OR₂) can be oriented in both syn and anti fashions when two adjacent phenylene rings are connected by the CH₃ bridge. This process, after ring closure of the linear pentamers, eventually leads to the formation of four P[₅] constitutional isomers (see panel b). The nearly statistical nature of this oligomerization/cyclization makes the desired tiara-P[₅] (T-P[₅]) with C₅ symmetry the least abundant product (~1/16th). To circumvent this, (see panel c) our "preoriented" strategy employs monomer M₅ with a hydroxymethylene handle. This handle directs the reaction to formation of all-syn linear pentamer (Pₛ₅) in the presence of a weak Lewis acid, resulting in T-P[₅] with high selectivity and yield.

![Figure 2](image-url)

Figure 2. (a) Rim-differentiated (propargyl)₅-T-P[₅] 2a and the other three constitutional isomers of (propargyl)₅-P[₅] isomers. HPLC chromatograms of mixtures of (propargyl)₅-P[₅] isomers obtained from (b) conventional statistical and (c) our "preoriented" synthesis. (d) ¹H NMR spectrum of 2a.

| Entry | Catalyst | Solvent | Time (hr) | Yield of Pₛ₅ (%) | Fraction of 2a (%) | Yield of 2a (%) |
|-------|----------|---------|-----------|-----------------|-------------------|---------------|
| 1     | BF₃·Et₂O | DCE     | 1         | 22              | 17                | 77            |
| 2     | AlCl₃    | DCE     | 1         | 16              | 20                | 3             |
| 3     | FeCl₃    | DCE     | 1         | 26              | 55                | 14            |
| 4     | FeBr₃    | DCE     | 1         | 24              | 54                | 13            |
| 5     | FeF₅     | DCE     | 1         | —               | —                 | —             |
| 6     | FeCl₂    | CH₂Cl₂  | 1         | 30              | 48                | 14            |
| 7     | FeCl₃    | CHCl₃   | 1         | 23              | 56                | 13            |
| 8     | FeCl₄    | DCE     | 4         | 33              | 54                | 18            |
| 9     | FeCl₅    | DCE     | 8         | 35              | 55                | 19            |

The reactions were performed by combining 1a (2.0 mmol) and catalyst (0.2 mmol, 10%) in solvent (10.0 mL) at room temperature.

Several other Lewis acids (AuCl₃, InCl₃, Sc(OTf)₃, ZnCl₂, AgOTf, CuOTf, CuCl₂, RuCl₃) were tested, but no P[₅] product was identified. No P[₅] product was isolated in reactions employing CH₃CN and THF as solvents. Isolated yield of four constitutional isomers combined. The yields in entries 6 to 9 were obtained from the average of at least three independent reactions. As determined by HPLC analysis. Based on the isolated yield of all P[₅] isomers and the fraction of T-P[₅] determined by HPLC analysis.

Table 1. Optimization of the Preoriented Synthetic Protocol of (propargyl)₅-Tiara-Pillar[₅]arene 2a

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several other metal salts (FeF\textsubscript{3}, AuCl\textsubscript{3}, InCl\textsubscript{3}, Sc(OTf)\textsubscript{3}, ZnCl\textsubscript{2}, the Lewis acid, the selectivity of T-P\textsubscript{5} blend of tubular stick and space-

were examined. Generally, chlorinated solvents lead to similar 
time was extended to 4 h (Table 1, Entry 8), the yield of P\textsubscript{5}s 
showed no enhancement (Table 1, Entry 9). The optimized 
improved slightly, but further elongation of the reaction time 
were subjected to the optimized reaction conditions. In general, rim-

deviation from the statistical protocol. Other Lewis acids (0.1 
achieved by 

other three non-T-P\textsubscript{5} constitutional isomers in the "preor-
rent strategy can be attributed to the parallel dealkylation/real-
side reactions on the hydroxymethylene handle of M\textsubscript{5} in the presence of Lewis acids (see Supporting Information Scheme S6). It is this dynamic covalent process which prevents the exclusive formation of the linear all-syn oligomeric intermediates.

The \textsuperscript{1}H NMR spectrum of (propargyl)\textsubscript{5}-T-P\textsubscript{5} 2a is shown in 
Figure 2d. The relatively simple spectrum without splitting in the 
aromatic region reflects the high C\textsubscript{5}-symmetry of this T-P\textsubscript{5} in 
solution. X-ray crystallography (Figure 3a) further unambigu-
ously confirms that all five propargyl constituents are positioned 
on the same rim of the P\textsubscript{5} scaffold.

In order to investigate the scope of this novel strategy, as well 
as to further increase the diversity of chemical functionalities on 
T-P\textsubscript{5} scaffolds, several different monomers containing either "clickable" moieties or good leaving groups were prepared. Specifi-
cally, monomers with allyl (1b), homoallyl (1c), 2-
bromoethyl (1d), and 3-bromopropyl (1e) moieties, were subjected to the optimized reaction conditions. In general, rim-
differentiated T-P\textsubscript{5}s 2b-2e were obtained in good isolated 
yields (up to ~20%; see Table 2, Entries 2 to 5). Furthermore, a

Table 2. Syntheses of Various Tiara-Pillar[5]arenes 2a−2f

| Entry | Substrate | R\textsuperscript{1}/R\textsuperscript{2} | Yield\textsuperscript{a} of P\textsubscript{5}s (%) | Yield\textsuperscript{b} of 2 (%) |
|-------|-----------|-------------------------|---------------------------|---------------------------|
| 1     | 1a'       | CH\textsubscript{2}=CH\textsubscript{2}/Me | 34                         | 19                         |
| 2     | 1b        | CH\textsubscript{2}CH=CH\textsubscript{2}/Me | 32                         | 16                         |
| 3     | 1c        | CH\textsubscript{2}=CH\textsubscript{2}/Me | 38                         | 18                         |
| 4     | 1d        | CH\textsubscript{2}Br/Me | 30                         | 15                         |
| 5     | 1e        | CH\textsubscript{2}CH=CH\textsubscript{2}/Me | 19                         | 9                          |
| 6     | 1f        | CH\textsubscript{2}CH=CH\textsubscript{2}/Me | 17                         | 8                          |

\textsuperscript{a} The reaction was performed by employing compounds 1a'−1f (2.0 mmol) and FeCl\textsubscript{3} (0.2 mmol, 10\%) in DCE (10.0 mL) for 4 h at room temperature. See Supporting Information for details. 
\textsuperscript{b} Isolated yields of four constitutional isomers combined. Yield of 2a is calculated based on the isolated yield of all P\textsubscript{5} isomers combined and the fraction of T-P\textsubscript{5} determined by HPLC analysis. Entries 2 to 6 are isolated yields of 2b−2f after flash chromatography.

"dual-functionalized" (propargyl)\textsubscript{5}(allyl)-T-P\textsubscript{5} 2f was success-
fully synthesized and isolated in 8\% yield (Table 2, Entry 6) using precursor 1f. The lower yields of 2e and 2f are presumably 
because of the steric hindrance caused by the relatively bulky 
groups attached to the monomer during the cyclization 
processes. All these T-P\textsubscript{5}s have the potential to be further 
derivatized through many routine reactions, including copper-
catalyzed azide−alkyne cycloaddition (CuAAC), thiol−yne−e 

"click" chemistry, alkene metathesis, as well as simple 
SN\textsubscript{2} reactions. For example, (3-azidopropyl)\textsubscript{5}-T-P\textsubscript{5} 3, which itself 
can be used in further CuAAC reactions, could be obtained (see Supporting Information) from reacting penta-bromide T-
P\textsubscript{5} 2e with NaN\textsubscript{3} in DMF in ~90\% yield. Single crystal samples 
of T-P\textsubscript{5}s, 2a−2f and 3, were obtained by slow vapor diffusion of hexane into ethyl acetate or dichloromethane solutions of the 
isolated compounds. The solid-state structures of T-P\textsubscript{5}s 2a−2f 
and 3, elucidated by X-ray crystallography (shown in Figure 3), 
again confirm their rim-differentiated nature. It is noteworthy 
that the X-ray snapshots of these T-P\textsubscript{5}s 2a−2f and 3 do not

Figure 3. Side and top views of X-ray solid-state structures of different tiara-pillar[5]arenes obtained by preoriented synthetic protocol, illustrated in a 
blend of tubular stick and space-filling representations: (a) (propargyl)\textsubscript{5}-T-P\textsubscript{5} (2a), (b) (allyl)-T-P\textsubscript{5} (2b), (c) (homoallyl)-T-P\textsubscript{5} (2c), (d) (2-
bromoethyl)-T-P\textsubscript{5} (2d), (e) (3-bromopropyl)-T-P\textsubscript{5} (2e), (f) (propargyl)(allyl)-T-P\textsubscript{5} (2f), and (g) (3-azidopropyl)-T-P\textsubscript{5} (3) (all T-PSs, 
apart from 2f, have five OCH\textsubscript{3} groups on the other rim). Only one of the two enantiomeric coconformations in the solid state is shown for each 
compound. All hydrogens and guest molecules are omitted for clarity. Color code: alkyl, purple; allyl, magenta; azido, green; bromine, orange; carbon, 
grey, oxygen, red.
have perfect C₂-symmetry in the solid state as a result of the different orientations adopted by the functional groups, whereas all pentagonal cavities were filled with hexane guest molecules inside (omitted in Figure 3 for clarity).

In summary, an FeCl₃-catalyzed cyclization of asymmetrically substituted 2,5-dialkoxybenzyl alcohols has been developed²⁵ for convenient and selective syntheses of rim-differentiated C₂-symmetric tiara-pillar[5]arenes. This preoriented synthetic protocol for tiara-pillar[5]arenes, which takes advantage of the hydroxyethylene handle to orient the oligomerization processes, pushes the selectivity to ~20%, both showing significant improvement from the results obtained by previous statistical syntheses. By applying this “preoriented” strategy, a series of tiara-pillar[5]arene derivatives was synthesized, isolated, and crystallized. Further studies toward expansion of chemical functionalities on tiara-pillar[5]arenes and their applications in supramolecular assemblies, bioconjugation, and surface functionalization are underway in our laboratories.

**ASSOCIATED CONTENT**

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.7b10767.

Synthetic procedures, HPLC analyses, mechanism and reaction pathways discussions (PDF)

Crystallographic Information (CIF)

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Notes

The authors declare no competing financial interest.

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**REFERENCES**

(1) Ogoshi, T.; Kanai, S.; Fujinami, S.; Yamagishi, T.; Nakamoto, Y. J. Am. Chem. Soc. 2008, 130, 5022–5023.

(2) (a) Xue, M.; Yang, X.; Chi, X.; Zhang, Z.; Huang, F. Acc. Chem. Res. 2012, 45, 1294–1308. (b) Ogoshi, T.; Yamagishi, T.; Nakamoto, Y. Chem. Rev. 2016, 116, 7937–8002.

(3) Pedersen, C. J. Angew. Chem., Int. Ed. Engl. 1988, 27, 1021–1027.

(4) Lehner, J. M. Angew. Chem., Int. Ed. Engl. 1988, 27, 89–112.

(5) Bruns, C.; Stoddart, J. F. The Nature of the Mechanical Bond; Wiley: Weinheim, 2017.

(6) (a) Cao, D.; Kou, Y.; Liang, J.; Chen, Z.; Wang, L.; et al. Angew. Chem., Int. Ed. 2009, 48, 9721–9723. (b) Ogoshi, T.; Aoki, T.; Kitajima, K.; Fujinami, S.; Yamagishi, T.; Nakamoto, Y. Acc. Chem. Res. 2011, 44, 1033–1043.

(7) Cram, D. J. Angew. Chem., Int. Ed. Engl. 1988, 27, 1009–1020.

(8) Strutt, N. L.; Zhang, H.; Schneebeli, S. T.; Stoddart, J. F. Acc. Chem. Res. 2014, 47, 2631–2642.

(9) (a) Szejtli, J. Chem. Rev. 1998, 98, 1743–1754. (b) Crini, G. Chem. Rev. 2014, 114, 10940–10975.

(10) Pedersen, C. J. J. Am. Chem. Soc. 1967, 89, 2495–2496.

(11) Freeman, W. A.; Mock, W. L.; Shih, N. Y. J. Am. Chem. Soc. 1981, 103, 7367–7368.

(12) Gutsche, C. D. Calixarenes Revisited; The Royal Society of Chemistry: Cambridge, 1998.

(13) (a) Ogoshi, T.; Umeda, K.; Yamagishi, T.; Nakamoto, Y. Chem. Commun. 2009, 4784–4786. (b) Ogoshi, T.; Shiga, R.; Hashizume, M.; Yamagishi, T. Chem. Commun. 2011, 47, 6927–6929. (c) Nierengarten, I.; Nothisen, M.; Sigwalt, D.; Biellmann, T.; Holler, M.; et al. Chem. Eur. J. 2013, 19, 17552–17558.

(14) (a) Strutt, N. L.; Forgan, R. S.; Spruell, J. M.; Botros, Y. Y.; Stoddart, J. F. J. Am. Chem. Soc. 2011, 133, 5668–5671. (b) Ogoshi, T.; Demachi, K.; Kitajima, K.; Yamagishi, T. Chem. Commun. 2011, 47, 7164–7166.

(15) (a) Zhang, Z.; Xia, B.; Han, C.; Yu, Y.; Huang, F. Org. Lett. 2010, 12, 3285–3287. (b) Strutt, N. L.; Fairen-Jimenez, D.; Iebl, J.; Lalonde, M. B.; Snurr, R. Q.; et al. J. Am. Chem. Soc. 2012, 134, 17436–17439.

(16) (a) Kou, Y.; Tao, H.; Cao, D.; Fu, Z.; Schollmeyer, D.; et al. Eur. J. Org. Chem. 2010, 2010, 6464–6470. (b) Zhang, Z.; Luo, Y.; Xia, B.; Han, C.; Yu, Y.; et al. Chem. Commun. 2011, 47, 2417–2419. (c) Yu, G.; Zhang, Z.; Han, C.; Xue, M.; Zhou, Q.; et al. Chem. Commun. 2012, 48, 2985–2986. (d) Shu, X.; Chen, W.; Hou, D.; Meng, Q.; Zheng, R.; et al. Chem. Commun. 2014, 50, 4820–4823. (e) Zhou, Y.; Yao, Y.; Huang, F. Chem. J. Chem. 2015, 33, 356–360.

(17) (a) Yao, Y.; Xue, M.; Chen, J.; Zhang, M.; Huang, F. J. Am. Chem. Soc. 2012, 134, 15712–15715. (b) Yu, G.; Ma, Y.; Han, C.; Yao, Y.; Tang, G.; et al. J. Am. Chem. Soc. 2013, 135, 10310–10313. (c) Zhang, H.; Ma, X.; Nguyen, K. T.; Zhao, Y. ACS Nano 2013, 7, 7853–7863.

(d) Nishimura, T.; Sanada, Y.; Matsu, S.; Okobira, T.; Mylonas, E.; et al. Chem. Commun. 2013, 49, 3052–3054. (e) Yao, Y.; Xue, M.; Zhang, Z.; Zhang, M.; Wang, Y.; et al. Chem. Sci. 2013, 4, 3667–3672.

(18) (a) Si, W.; Chen, L.; Hu, X.-B.; Tang, G.; Chen, Z.; et al. Angew. Chem. Int. Ed. 2011, 50, 12564–12568. (b) Xu, B.; Chen, Z.; Tang, G.; Hou, J.-L.; Li, Z.-T. J. Am. Chem. Soc. 2012, 134, 8384–8387.

(c) Chen, L.; Si, W.; Zhang, L.; Tang, G.; Li, Z.-T.; et al. J. Am. Chem. Soc. 2013, 135, 2152–2155.

(19) (a) Pujari, S. P.; Scheres, L.; Marcelis, A. T. M.; Zuilhof, H. Angew. Chem. Int. Ed. 2014, 53, 6322–6336. (b) de Smet, L. C. P. M.; Pukin, A. V.; Sun, Q.-Y.; Eves, B. J.; Lopinski, G. P.; et al. Appl. Surf. Sci. 2005, 252, 24–30. (c) Escorihuela, J.; Zuilhof, H. J. Am. Chem. Soc. 2017, 139, 5870–5876.

(20) Luo, L.; Nie, G.; Tian, D.; Deng, H.; Jiang, L.; et al. Angew. Chem., Int. Ed. 2016, 55, 12713–12716.

(21) Zhou, J.; Chen, M.; Xie, J.; Diao, G. ACS Appl. Mater. Interfaces 2013, 5, 11218–11224.

(22) Ma, Y.; Zhang, Z.; Ji, X.; Han, C.; He, J.; et al. J. Eur. Org. Chem. 2011, 2011, 5331–5335.

(23) After the acceptance of this manuscript, it was brought to our attention that a similar protocol was developed independently by Professor Da Ma’s group. See Ding, J.; Chen, J.; Mao, W.; Huang, J.; Ma, D. Org. Biomol. Chem. 2017, 15, 7894–7897.

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