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C_3-Symmetric Chiral Cage-Shaped Phosphates: Synthesis and Application as Organocatalysts in Asymmetric Iodolactonizations

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Dedicated to the memory of Professor Masahiko Iyoda

C_3-symmetric chiral cage-shaped phosphates that contain either a C—H or Si—Me tethered group were successfully synthesized. These phosphates were found to be air-stable Lewis-basic catalysts in enantioselective iodolactonization reactions where, I_2 is activated with 1,3-dichloro-5,5-dimethylhydantoin (DCDMH). The C—H-tethered phosphate demonstrated efficient catalytic activity with good enantioselectivity for the iodolactonization of pent-4-enoic acids. In contrast, the Si—Me-tethered phosphate was effective in the enantioselective iodolactonization of hex-5-enoic acids, yielding six-membered iodolactones.

1. Introduction

In organic chemistry, molecular symmetry is one of the most crucial factors for determining not only the chemical and physical properties of a molecule,[1,2] but also for controlling its reactivity and the selectivity of its reactions through a specific steric and/or electronic reaction field.[3,4] The design of the molecular skeletons of asymmetric catalysts that can achieve high enantioselectivity has been the subject of intense research efforts. As such, chiral ligands and catalysts possessing C_2 rotational symmetry have emerged as the most fundamental yet promising scaffolds and have been developed and applied to various asymmetric syntheses.[5–9] However, compared to the abundant number of chiral catalysts with C_2 symmetry, research on catalysts with higher rotational symmetry has lagged behind, even though C_3-symmetric molecules represent intriguing potential alternatives to C_2-symmetric chiral catalysts. Accordingly, the exploration of new chiral scaffolds with rotational symmetry higher than C_2 is in high demand.[10] Some C_3-symmetric molecules[11–14] have been developed as asymmetric catalysts,[15–18] for use in molecular recognition,[19,20] and in materials science.[21–23] The application of C_3-symmetric chiral molecules to organocatalysis[24–30] has been an important area of research for these molecules. For example, C_3-symmetric chiral trisimidazoline **1** has been used as an enantioselective catalyst in bromolactonization reactions (Figure 1a).[31,32]

Phosphate esters and amides are common structures found in organophosphorus(V) compounds. The P═O group acts as an *n*-type Lewis-basic moiety that can catalytically activate reactions by interacting with an electron-accepting atom in one of the reagents or substrates.[33,34] Moreover, introducing a chiral moiety into the phosphate group allows for the development of effective chiral Lewis-basic catalysts. Various phosphate derivatives have been used as catalysts, enabling enantioselective versions of reactions such as selenolactonization,[35] halocyclization,[36–42] and sulfenocyclization.[43–49]

In our group, we have discovered various C_3-symmetric cage-shaped Lewis acids that incorporate aluminum aryloxides,[50,51] borates,[51–56] and heavier group-14 elements.[57] Recently, we have expanded this C_3-symmetric ligand design to include a Lewis base, resulting in C_3-symmetric cage-shaped phosphites **2a**P and **2b**P (Figure 1b).[58] The two cage-shaped phosphites **2a**P and **2b**P serve as chiral ligands in a Rh-catalyzed asymmetric conjugate addition, giving products in acceptable yield with excellent enantioselectivity. The Lewis basicity of **2a**P and **2b**P can be controlled by the differences in their steric bulk caused by the tethered C—H and Si—Me groups. These findings inspired us to replace the phosphite moiety of **2**P with a phosphate, and to explore the catalytic activity of the obtained **2**P═O molecules as chiral Lewis bases. Kawashima and co-workers have reported a related phosphate and, whilst they demonstrated its C_{60}-inclusion behavior, its catalytic activity remains unexplored.[59]

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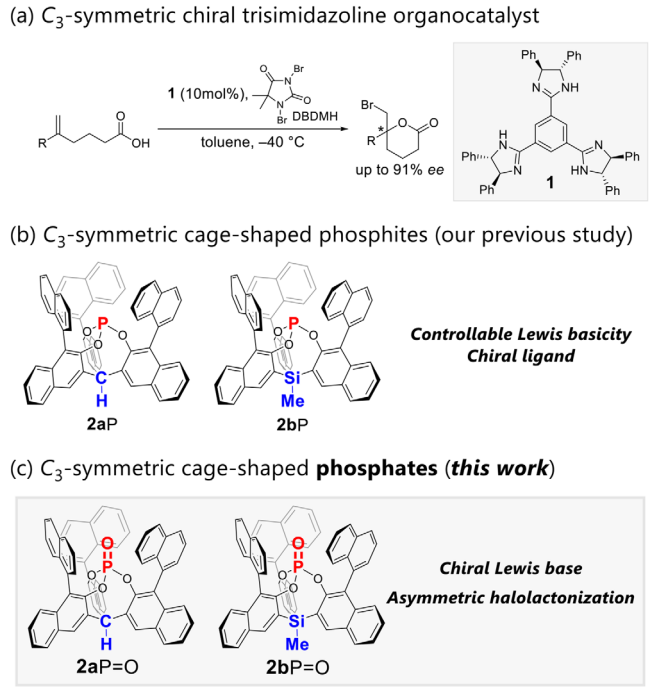
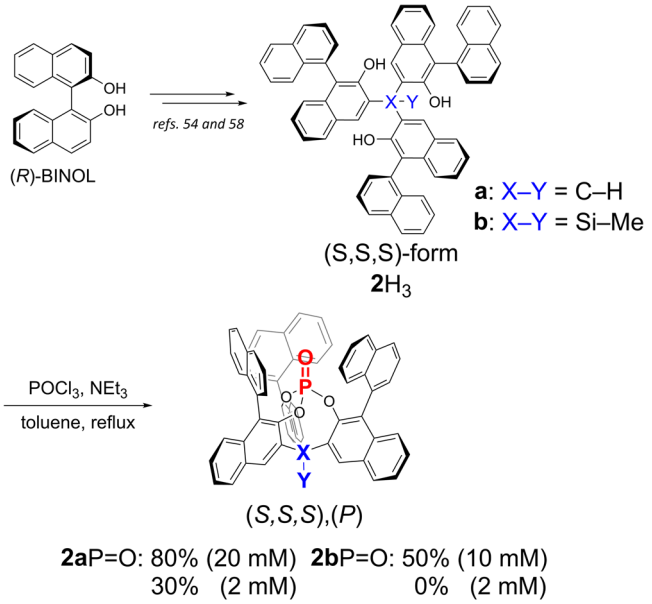


Figure 1. (a) C_3-symmetric chiral trisimidazoline **1** applied in an asymmetric bromolactonization. (b) Cage-shaped phosphites **2**P. (c) This work: cage-shaped phosphates **2**P=O.



Scheme 1. Synthetic route to C_3-symmetric cage-shaped phosphates **2a**P=O and **2b**P=O.

Herein, we describe the synthesis and catalytic activity of C_3-symmetric chiral cage-shaped phosphates **2a**P=O and **2b**P=O. Our chiral cage-shaped phosphates **2a**P=O and **2b**P=O catalyze asymmetric iodolactonizations[10] of pent-4-enoic acids and hex-5-enoic acids. The distinct steric environments of the two **2**P=O catalysts result in varying degrees of enantioselectivity depending on the substrates employed.

2. Results and Discussion

The synthetic route to obtain the cage-shaped phosphates **2**P=O is depicted in Scheme 1. According to the protocol from our previous study, carbon-tethered **2a**H_3[54] and silicon-tethered **2b**H_3[58] were synthesized starting from (*R*)-BINOL. To construct the cage-shaped framework, the conditions reported by Kawashima[59] were employed. For that purpose, one equiv of phosphoryl chloride was added to a dilute solution of **2a**H_3 in toluene (2 mM) in the presence of Et_3N (10 equiv). The reaction mixture was refluxed for 20 h to give carbon-tethered **2a**P=O in 30% yield. However, silicon-tethered **2b**P=O could not be obtained under the same reaction conditions. Thus, we modified the concentration of the reaction mixture and performed the reaction under harsher conditions. Specifically, a more concentrated reaction mixture containing **2b**H_3 (20 mM) and phosphoryl chloride in toluene was sealed in a Schlenk flask with a J-Young tap and was heated at 125 °C for two days, yielding silicon-tethered **2b**P=O in moderate yield (50%). Applying the new conditions to the synthesis of **2a**P=O improved the yield to 80%. The obtained cage-shaped phosphates **2a**P=O and **2b**P=O are bench-stable colorless solids and can be purified using silica-gel-column chromatography. The stability of the **2**P=O molecules stands in contrast to that of the **2**P phosphites, which quickly decompose under ambient conditions.

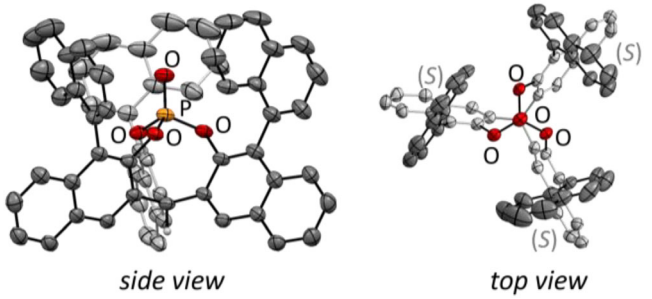
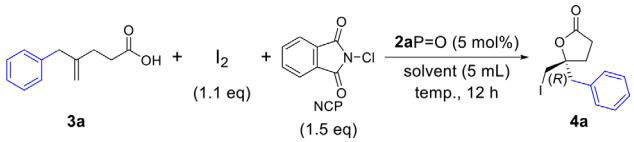


Figure 2. Molecular structure of cage-shaped phosphate **2a**P=O with thermal ellipsoids at 50% probability;[70] some hydrogen atoms are omitted for clarity.

A single-crystal X-ray diffraction analysis of carbon-tethered **2a**P=O confirmed the presence of the C_3-symmetric cage-shaped structure. Gradual evaporation of a solution of **2a**P=O in CH_3CN afforded single crystals suitable for a crystallographic analysis and the thermal-ellipsoid plots are shown in Figure 2. A robust C_3-symmetric structure is created by the three naphthyl groups. All binaphthyl axes have (*S*) configurations and the helical structure formed around the phosphate is of the (*P*)-type. Selected geometric parameters obtained from the crystal structure are summarized in Table S1. The P=O bond (1.448(3) Å) is comparable to that of triphenyl phosphate (1.432 Å).[60] Although determining the molecular structure of silicon-tethered **2b**P=O via a crystallographic analysis failed due to its poor crystallinity, spectroscopic analytical techniques, including ^{1}H, ^{13}C, ^{29}Si, and ^{31}P NMR spectroscopy and high-resolution mass spectrometry (HRMS) measurements, confirmed the successful formation of **2b**P=O. The ^{31}P NMR chemical shifts of **2a**P=O (−19.4 ppm)

Table 1. Enantioselective iodolactonization of **3a** with I_2 in the presence of NCP catalyzed by **2a**P=O.[a)]



Entry	Temp. (°C)	Solvent	Yield (%)[b)]	*ee* (%)[b)]
1	r.t.	Toluene	97	9
2	0	Toluene	84	17
3	−20	Toluene	96	28
4	−40	Toluene	62	43
5	−60	Toluene	21	58
6	−78	Toluene	3	65
7	−78	CH_2Cl_2	64	15
8	−78	Et_2O	52	0
9	−78	THF	100	0

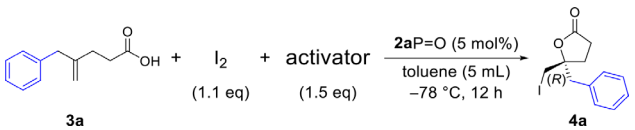
[a)] I_2, NCP, and **2a**P=O were stirred in toluene at −78 °C for 1 h prior to addition of **3a**. [b)] Yield and *ee* values were determined via ^{1}H NMR measurements and chiral HPLC analyses, respectively.

and **2b**P=O (−25.8 ppm) are up-field shifted compared to those of the corresponding phosphites **2a**P (108.4 ppm) and **2b**P (111.2 ppm). Moreover, the phosphorous center of **2**P=O should be magnetically shielded by the three surrounding naphthyl groups, resulting in an up-field shift compared to open-caged triphenyl phosphate (−17.0 ppm).

Then, we examined the ability of the chiral Lewis-basic phosphates **2**P=O to catalyze an asymmetric synthetic reaction. As a model transformation, we selected the iodolactonization of 4-benzylpent-4-enoic acid (**3a**) with I_2 in the presence of an *N*-chlorophthalimide (NCP) activator.[39,61,62] Using **2a**P=O as a chiral basic catalyst in the presence of NCP, the asymmetric addition of I_2 to **3a** to produce **4a** was performed (Table 1). The reaction in toluene at 25 °C smoothly afforded **4a** in 97% yield, albeit that the enantioselectivity was very poor (9% enantiomeric excess (*ee*) of the (*R*)-stereoisomer;[39] entry 1, Table 1). Lowering the reaction temperature from 25 °C to −78 °C effectively improved the enantioselectivity up to 65% *ee* (entries 2–6, Table 1). However, the yield of **4a** at −78 °C was significantly suppressed (3%). More polar solvents, such as CH_2Cl_2, Et_2O, and THF, yielded a lower *ee* or a racemic mixture in moderate to high yield (entries 7–9, Table 1). The reactivity and enantioselectivity of the reaction were found to be dramatically depended on the solvent polarity. These features are consistent with Ishihara's finding that polar solvent systems impede the generation of active ionic species.[63]

Next, we screened the I_2 activator to achieve both a good yield and enantioselectivity for the iodolactonization of **3a** at low temperature (Table 2). First, *N*-iodosuccinimide (NIS) was utilized instead of NCP (entry 1, Table 2). Although the enantioselectivity was comparable to that of NCP (63% *ee*), the yield of **4a** remained poor (8%). Interestingly, *N*-bromosuccinimide (NBS), which is known to be a more reactive activator for halocyclization,[40] furnished **4a** quantitatively

Table 2. Optimization of the I_2 activator[a)].



Entry	Activator	Yield (%)[b)]	*ee* (%)[b)]
1	NIS	8	63
2	NBS	100	53
3	DBDMH	60	19
4	NBP	72	37
5	NBA	80	0
6	NCS	8	75
7	DCDPH	52	62
8	DCDMH	56	76
9		100	8
10		60	10
11		71	8
12		12	70

[a)] I_2, activator, and **2a**P=O were stirred in toluene at −78 °C for 1 h prior to addition of **3a**. [b)] Yield and *ee* values were determined via ^{1}H NMR measurements and chiral HPLC analyses, respectively.

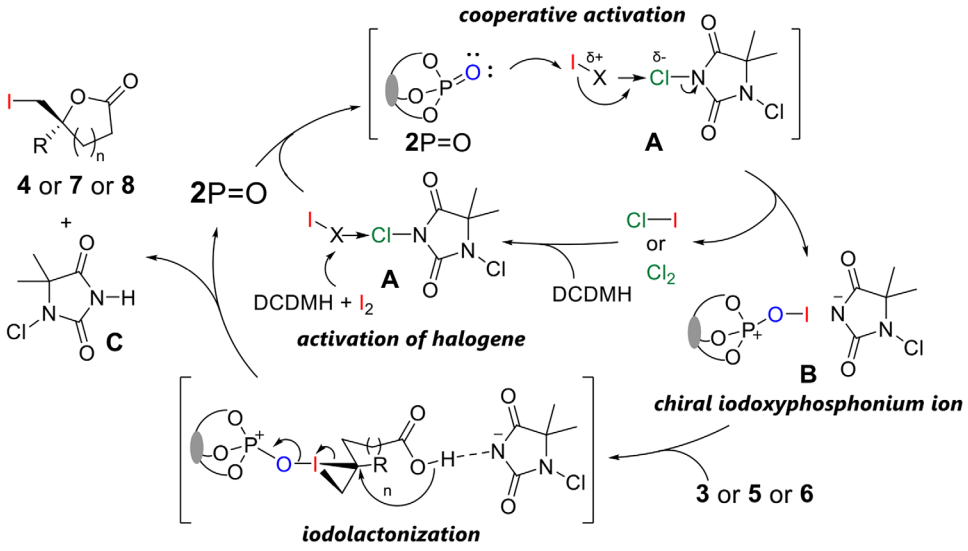


Figure 3. Proposed mechanism of the chiral iodolactonization catalyzed by **2**P═O.

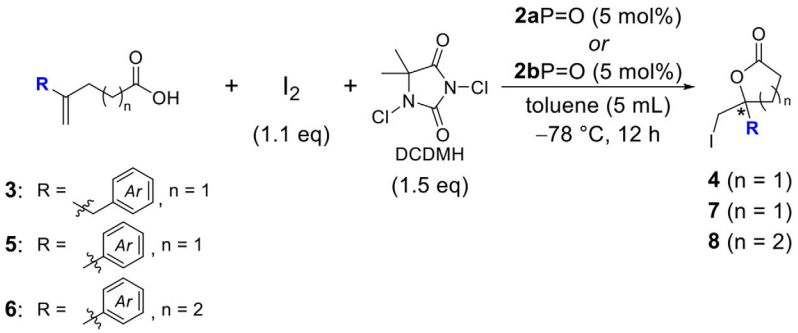
with a moderate enantioselectivity (entry 2, Table 2). According to a report by Ishihara, *N*-bromoimides can generate a more electrophilic ion pair with I_2 with the assistance of a Lewis-basic phosphonium catalyst.[40] Although this insight raised the expectation that *N*-bromoimides may serve as good activators, other related reagents, including 1,3-dibromo-5,5-dimethylhydantoin (DBDMH), *N*-bromophthalimide (NBP), and *N*-bromoacetamide (NBA), afforded **4a** in moderate yield with low enantioselectivity compared to NBS (entries 3–5, Table 2). Next, we shifted our focus on *N*-choloroimides. Despite the low yield of the reaction, *N*-chlorosuccinimide (NCS) improved the enantioselectivity to 75% *ee* (entry 6, Table 2). In this case, we presume that a slow release of a chiral iodoxyphosphonium ion active species is responsible for the enhanced enantioselectivity.[39]

Importantly, 1,3-dichloro-5,5-diphenylhydantoin (DCDPH; entry 7, Table 2) and 1,3-dichloro-5,5-dimethylhydantoin (DCDMH; entry 8, Table 2) improved both the yield and enantioselectivity of **4a** at −78 °C. *N*-chloro-2-pyrrolidone (entry 9, Table 2), *N*-chlorosaccharin (entry 10, Table 2), and trichloroisocyanuric acid (entry 11, Table 2) afforded **4a** in satisfactory yield but poor enantioselectivity. In contrast, *N*-chloro-1,8-naphthalimide (entry 12, Table 2) exhibited poor reactivity but high enantioselectivity. Of the tested activators, DCDMH (entry 8, Table 2) showed the best balance between reactivity and enantioselectivity.

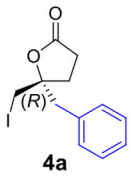
Based on a report by Ishihara,[39] a plausible catalytic cycle is shown in Figure 3. Initially, the Lewis-acidic DCDMH might activate I_2 through halogen-bonding interactions to form the active iodinating species **A**. The cooperative activation of **A** with phosphate **2**P═O would then afford the chiral iodoxyphosphonium ion **B** as an active species. Finally, electrophilic iodination of the double bond of the substrate followed by cyclization would provide the desired iodolactones **4**/**7**/**8** and imide **C**. Our catalysts are stable under the reaction conditions and can be recovered from the reaction mixture using silica-gel column chromatography.

With the optimized conditions in hand, pent-4-enoic acids (**3** and **5**) and hex-5-enoic acids (**6**) were examined (Scheme 2). The reactions of the pent-4-enoic acids with 4-methylbenzyl (**3b**) and 4-methoxybenzyl (**3c**) groups, catalyzed by **2a**P═O, furnished **4b** and **4c**, respectively, in moderate yield with decreased enantioselectivity relative to **3a** (Scheme 2a). Using **2b**P═O as the Lewis-basic catalyst resulted in poor enantioselectivity, even though the yield of the products was improved. The same trends regarding reactivity and enantioselectivity were observed for the iodolactonization of **3d** and **3e** with 2- or 4-fluorobenzyl groups, respectively. A comparison of the two catalysts showed that the carbon-tethered cage-shaped phosphate **2a**P═O affords the products with better enantioselectivity (**4e**: 70% *ee*) than its silicon-tethered counterpart **2b**P═O (**4e**: 22% *ee*).

The iodolactonizations of 4-arylpent-4-enoic acid derivatives (**5**) catalyzed by **2a**P═O gave the corresponding products (**7**) in moderate enantioselectivity (46%–68% *ee* of the (*R*)-stereoisomers;[39,64] Scheme 2b). Substrates with phenyl (**5a**), 4-chlorophenyl (**5b**), and 4-methylphenyl (**5c**) groups were tolerated under the applied conditions, yielding the corresponding products with moderate enantioselectivity. However, the pent-4-enoic acid with a 4-methoxyphenyl group (**5d**) afforded a racemic product probably because the electron-donating 4-methoxy group assists the generation of a cationic intermediate, leading to a competing background process. In comparison, the enantioselectivity of the corresponding reactions driven by **2b**P═O were inferior. According to a previous report, controlling the enantioselectivity of the iodolactonization of 4-aryllpent-4-enoic acid derivatives **5** using a phosphate-based Lewis-basic catalyst is challenging.[40] Highly reactive benzyl cations of these substrates are generated as intermediates of the iodolactonization, resulting in a direct iodolactonization. Chiral iodoxyphosphonium ion **B** (Figure 3) is not involved in the direct iodolactonization, and hence no enantioselectivity was observed. However, our carbon-tethered phosphate **2a**P═O attained respectable enantioselectivity.

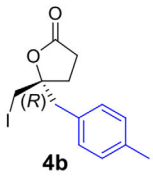


(a) Pent-4-enoic acids with a benzyl-type substituent



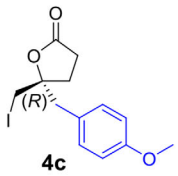
4a

2aP=O: 56%, 76% *ee*
2bP=O: 65%, 22% *ee*



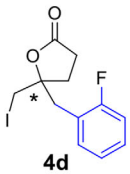
4b

2aP=O: 45%, 31% *ee*
2bP=O: 80%,15% *ee*



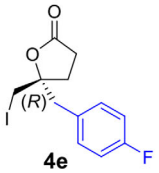
4c

2aP=O: 58%, 27% *ee*
2bP=O: 80%, 8% *ee*



4d

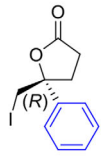
2aP=O: 10%, 35% *ee*
2bP=O: 50%, 12% *ee*



4e

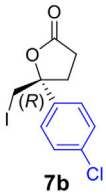
2aP=O: 40%, 70% *ee*
2bP=O: 100%, 22% *ee*

(b) Pent-4-enoic acids with an aryl-type substituent



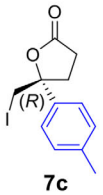
7a

2aP=O: 20%, 68% *ee*
2bP=O: 37%, 29% *ee*



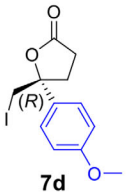
7b

2aP=O: 5%, 46% *ee*
2bP=O: 50%, 0% *ee*



7c

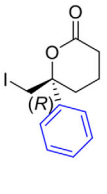
2aP=O: 30%, 67% *ee*
2bP=O: 30%, 32% *ee*



7d

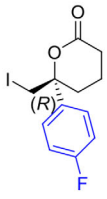
2aP=O: 30%, 0% *ee*
2bP=O: 23%, 0% *ee*

(c) Hex-5-enoic acids with an aryl-type substituent



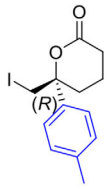
8a

2aP=O: 40%, 0% *ee*
2bP=O: 50%, 46% *ee*



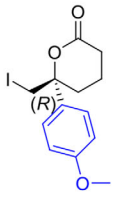
8b

2aP=O: trace, 0% *ee*
2bP=O: 30%, 49% *ee*



8c

2aP=O: trace, 0% *ee*
2bP=O: 40%, 28% *ee*



8d

2aP=O: 64%, 0% *ee*
2bP=O: 67%, 0% *ee*

Scheme 2. Enantioselective iodolactonization of **3**, **5**, and **6** catalyzed by **2a**P═O and **2b**P═O. Yield and *ee* values of products were determined via ^{1}H NMR measurements and chiral HPLC analyses, respectively.

Interestingly, the iodolactonization of hex-5-enoic acid derivatives (**6**) was smoothly catalyzed by silicon-tethered cage-shaped phosphate **2b**P═O instead of by carbon-tethered **2a**P═O (Scheme 2c). The reactions of the hex-5-enoic acids with phenyl (**6a**), 4-fuluorophenyl (**6b**), and 4-methylphenyl (**6c**) groups catalyzed by **2b**P═O furnished the corresponding six-membered lactones (**8a**–**8c**) in moderate yield (30%–50%) and enantiomeric excesses (28%–46% *ee* of the (*R*)-stereoisomer),[65] while the hex-5-enoic acid substrate containing a 4-methoxyphenyl group (**6d**) afforded a racemic product.

Based on our previous study of the cage-shaped phosphites **2**P,[58] the enantioselective formation of a product with a larger ring is more affected by steric demand. Therefore, it is reasonable to believe that bulkier **2b**P═O has a greater activation energy than **2a**P═O in reactions with substrate **6**.

3. Conclusion

In conclusion, we have synthesized two chiral C_3-symmetric cage-shaped phosphates and applied them as catalysts in the asymmetric iodolactonization of pent-4-enoic acid and hex-5-enoic acid derivatives. The I_2 activator 1,3-dichloro-5,5-dimethylhydantoin (DCDMH) successfully balances the chemical reactivity and enantioselectivity of this catalytic reaction system. The Lewis basicity and chemical environment of the **2**P═O catalysts were precisely controlled by changing the tethered group of each catalyst. Cage-shaped phosphates **2a**P═O and **2b**P═O exhibit complementary catalytic activity, that is, carbon-tethered **2a**P═O shows superior enantioselectivity for the formation of 5-membered ring products **4** and **7**, whereas, silicon-tethered **2b**P═O was suitable for the enantioselective formation of 6-membered ring product **8**. The phosphates presented here can be expected to serve as a basic template for the creation of new chiral C_3-symmetric Lewis-basic catalysts.

4. Experimental Section

All synthetic procedures and characterization data for unknown compounds are provided in the Supporting Information. The data that support the findings of this study are available in the Supporting Information associated with this article.

Supporting Information

The authors have cited additional references within the Supporting Information.[66–69]

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Conflict of Interests

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supporting Information of this article.;

Keywords: C_3-symmetric ligands · Cage-shaped phosphates · Chiral Lewis bases · Halogen reagents · Iodolactonization

[1] In *Mol. Symmetry*, John Wiley & Sons, Ltd, Hoboken, **2009**, pp. 45–74.
[2] In *Mol. Symmetry*, John Wiley & Sons, Ltd, Hoboken, **2009**, pp. 219–297.
[3] C. Moberg, *Bull. Chem. Soc. Jpn.* **2021**, *94*, 558–564.
[4] C. Moberg, *Isr. J. Chem.* **2012**, *52*, 653–662.
[5] J. K. Whitesell, *Chem. Rev.* **1989**, *89*, 1581–1590.
[6] A. Pfaltz, W. J. Drury, *Proc. Nat. Acad. Sci* **2004**, *101*, 5723–5726.
[7] J.-H. Xie, Q.-L. Zhou, *Acc. Chem. Res.* **2008**, *41*, 581–593.
[8] K. Ding, Z. Han, Z. Wang, *Chem. Asian J.* **2009**, *4*, 32–41.
[9] F. Yang, J.-H. Xie, Q.-L. Zhou, *Acc. Chem. Res.* **2023**, *56*, 332–349.
[10] G. E. Veitch, E. N. Jacobsen, *Angew. Chem. Int. Ed. Engl.* **2010**, *49*, 7332–7335.
[11] C. Moberg, *Angew. Chem. Int. Ed. Engl.* **1998**, *37*, 248–268.
[12] S. E. Gibson, M. P. Castaldi, *Chem. Commun.* **2006**, 3045.
[13] S. E. Gibson, M. P. Castaldi, *Angew. Chem. Int. Ed. Engl.* **2006**, *45*, 4718–4720.
[14] C. Moberg, *Angew. Chem. Int. Ed. Engl.* **2006**, *45*, 4721–4723.
[15] G. Bringmann, R.-M. Pfeifer, C. Rummey, K. Hartner, M. Breuning, *J. Org. Chem.* **2003**, *68*, 6859–6863.
[16] K. Murai, S. Fukushima, A. Nakamura, M. Shimura, H. Fujioka, *Tetrahedron* **2011**, *67*, 4862–4868.
[17] S. Bellemin-Laponnaz, L. H. Gade, *Angew. Chem. Int. Ed. Engl.* **2002**, *41*, 3473–3475.
[18] J. N. Moorthy, S. Saha, *Eur. J. Org. Chem.* **2010**, *2010*, 6359–6365.
[19] J. Chin, C. Walsdorff, B. Stranix, J. Oh, H. J. Chung, S. Park, K. Kim, *Angew. Chem. Int. Ed. Engl.* **1999**, *38*, 2756–2759.
[20] S.-G. Kim, K.-H. Kim, Y. K. Kim, S. K. Shin, K. H. Ahn, *J. Am. Chem. Soc.* **2003**, *125*, 13819–13824.
[21] J. van Gestel, A. R. A. Palmans, B. Titulaer, J. A. J. M. Vekemans, E. W. Meijer, *J. Am. Chem. Soc.* **2005**, *127*, 5490–5494.
[22] M. L. Bushey, T.-Q. Nguyen, W. Zhang, D. Horoszewski, C. Nuckolls, *Angew. Chem. Int. Ed. Engl.* **2004**, *43*, 5446–5453.
[23] T. Kubo, S. Miyazaki, T. Kodama, M. Aoba, Y. Hirao, H. Kurata, *Chem. Commun.* **2015**, *51*, 3801–3803.
[24] B. List, *Chem. Rev.* **2007**, *107*, 5413–5415.
[25] S. Mukherjee, J. W. Yang, S. Hoffmann, B. List, *Chem. Rev.* **2007**, *107*, 5471–5569.
[26] M. J. Gaunt, C. C. C. Johansson, *Chem. Rev.* **2007**, *107*, 5596–5605.
[27] T. Hashimoto, K. Maruoka, *Chem. Rev.* **2007**, *107*, 5656–5682.
[28] T. Akiyama, *Chem. Rev.* **2007**, *107*, 5744–5758.

[29] S.-H. Xiang, B. Tan, *Nat. Commun.* **2020**, *11*, 3786.
[30] O. García Mancheño, M. Waser, *Eur. J. Org. Chem.* **2023**, *26*, e202200950.
[31] K. Murai, T. Matsushita, A. Nakamura, S. Fukushima, M. Shimura, H. Fujioka, *Angew. Chem. Int. Ed. Engl.* **2010**, *49*, 9174–9177.
[32] K. Murai, A. Nakamura, T. Matsushita, M. Shimura, H. Fujioka, *Chem. Eur. J.* **2012**, *18*, 8448–8453.
[33] S. E. Denmark, G. L. Beutner, *Angew. Chem. Int. Ed. Engl.* **2008**, *47*, 1560–1638.
[34] X. Liu, L. Lin, X. Feng, *Chem. Commun.* **2009**, 6145.
[35] S. E. Denmark, W. R. Collins, *Org. Lett.* **2007**, *9*, 3801–3804.
[36] A. Matviitsuk, S. E. Denmark, *Angew. Chem. Int. Ed. Engl.* **2019**, *58*, 12486–12490.
[37] S. E. Denmark, M. T. Burk, *Org. Lett.* **2012**, *14*, 256–259.
[38] S. E. Denmark, P. Ryabchuk, M. T. Burk, B. B. Gilbert, *J. Org. Chem.* **2016**, *81*, 10411–10423.
[39] H. Nakatsuji, Y. Sawamura, A. Sakakura, K. Ishihara, *Angew. Chem. Int. Ed. Engl.* **2014**, *53*, 6974–6977.
[40] Y. Lu, H. Nakatsuji, Y. Okumura, L. Yao, K. Ishihara, *J. Am. Chem. Soc.* **2018**, *140*, 6039–6043.
[41] Y. Tsuji, K. Kon, T. Horibe, K. Ishihara, *Chem. Asian J.* **2023**, *18*, e202300019.
[42] R. C. Samanta, H. Yamamoto, *J. Am. Chem. Soc.* **2017**, *139*, 1460–1463.
[43] S. E. Denmark, A. Jaunet, *J. Am. Chem. Soc.* **2013**, *135*, 6419–6422.
[44] K. M. Hilby, S. E. Denmark, *J. Org. Chem.* **2021**, *86*, 14250–14289.
[45] T. Menard, A. Laverny, S. E. Denmark, *J. Org. Chem.* **2021**, *86*, 14290–14310.
[46] S. E. Denmark, E. Hartmann, D. J. P. Kornfilt, H. Wang, *Nat. Chem.* **2014**, *6*, 1056–1064.
[47] Z. Tao, K. A. Robb, K. Zhao, S. E. Denmark, *J. Am. Chem. Soc.* **2018**, *140*, 3569–3573.
[48] S. E. Denmark, D. J. P. Kornfilt, T. Vogler, *J. Am. Chem. Soc.* **2011**, *133*, 15308–15311.
[49] S. E. Denmark, H. M. Chi, *J. Am. Chem. Soc.* **2014**, *136*, 8915–8918.
[50] A. Konishi, H. Nakajima, H. Maruyama, S. Yoshioka, A. Baba, M. Yasuda, *Polyhedron* **2017**, *125*, 130–134.
[51] D. Tanaka, Y. Kadonaga, Y. Manabe, K. Fukase, S. Sasaya, H. Maruyama, S. Nishimura, M. Yanagihara, A. Konishi, M. Yasuda, *J. Am. Chem. Soc.* **2019**, *141*, 17466–17471.
[52] M. Yasuda, S. Yoshioka, S. Yamasaki, T. Somyo, K. Chiba, A. Baba, *Org. Lett.* **2006**, *8*, 761–764.
[53] H. Nakajima, M. Yasuda, R. Takeda, A. Baba, *Angew. Chem. Int. Ed. Engl.* **2012**, *51*, 3867–3870.
[54] A. Konishi, K. Nakaoka, H. Maruyama, H. Nakajima, T. Eguchi, A. Baba, M. Yasuda, *Chem. Eur. J.* **2017**, *23*, 1273–1277.
[55] D. Tanaka, Y. Tsutsui, A. Konishi, K. Nakaoka, H. Nakajima, A. Baba, K. Chiba, M. Yasuda, *Chem. Eur. J.* **2020**, *26*, 15023–15034.
[56] Y. Tsutsui, D. Tanaka, Y. Manabe, Y. Ikinaga, K. Yano, K. Fukase, A. Konishi, M. Yasuda, *Chem. A Eur. J.* **2022**, *28*, e202202284.
[57] D. Tanaka, A. Konishi, M. Yasuda, *Chem. Asian J.* **2021**, *16*, 3118–3123.
[58] X. Liu, K. Tomita, A. Konishi, M. Yasuda, *Chem. A Eur. J.* **2023**, *29*, e202302611.
[59] J. Kobayashi, Y. Domoto, T. Kawashima, *Chem. Lett.* **2010**, *39*, 134–135.
[60] G. W. Svetich, C. N. Caughlan, *Acta Crystallogr.* **1965**, *19*, 645–650.
[61] A. Sakakura, K. Ishihara, *Chem. Rec.* **2015**, *15*, 728–742.
[62] R. Kristianslund, J. E. Tungen, T. V. Hansen, *Org. Biomol. Chem.* **2019**, *17*, 3079–3092.
[63] A. Sakakura, A. Ukai, K. Ishihara, *Nature* **2007**, *445*, 900–903.
[64] R. Nishiyori, K. Okuno, B. Chan, S. Shirakawa, *Chem. Pharm. Bull.* **2022**, *70*, c22-00049.
[65] J. E. Tungen, J. M. J. Nolsøe, T. V. Hansen, *Org. Lett.* **2012**, *14*, 5884–5887.
[66] O. V. Dolomanov, L. J. Bourhis, R. J. Gildea, J. A. K. Howard, H. Puschmann, *J. Appl. Crystallogr.* **2009**, *42*, 339–341.
[67] J. Haas, S. Piguel, T. Wirth, *Org. Lett.* **2002**, *4*, 297–300.
[68] T. Arai, N. Sugiyama, H. Masu, S. Kado, S. Yab, M. Yamanaka, *Chem. Commun.* **2014**, *50*, 8287–8290.
[69] M. Ramillien, N. Vanthuyne, M. Jean, D. Gherase, M. Giorgi, J.-V. Naubron, P. Piras, C. Roussel, *J. Chromatogr. A* **2012**, *1269*, 82–93.
[70] Deposition Number(s) " https://www.ccdc.cam.ac.uk/services/structures?id = https://doi.org/10.1002/ajoc.202500299 ">2426798 (for 2 = " http://www.ccdc.cam.ac.uk/structures ">Access Structures service).

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