Generation of Allenyliodinanes and Their Reductive Iodonio-Claisen Rearrangement

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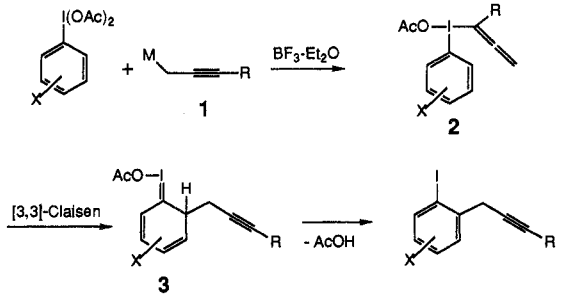
Abstract: Reported for the first time are the generation of allenyliodinanes and their reductive iodonio-Claisen rearrangement. Reaction of propargylsilanes, germanes, and stannanes with aryliodinanes in the presence of BF_3–Et_2O undergoes a reductive iodonio-Claisen rearrangement under mild conditions, yielding *o*-propargyliodoarenes in good yields. The reductive ortho propargylation probably involves the intermediate formation of allenyl(aryl)iodinanes, which undergo [3,3]-sigmatropic rearrangement. The lack of crossover products argues for the intramolecularity of the rearrangement. When both ortho positions of aryliodinanes are occupied with alkyl substituents, the reductive iodonio-Claisen rearrangement affords meta substitution products. This is the first to show that meta-Claisen rearrangement occurs preferentially even when a free para position is available. The reductive ortho propargylation of iodinanes takes place under much milder conditions than the Claisen rearrangement. The lower activation energy associated with the iodonio-Claisen rearrangement of allenyl(aryl)iodinanes can be interpreted in terms of the small bond energy of the breaking apical carbon–iodine(III) bond.

Allenyliodinanes are a new class of hypervalent organoiodinanes, and their synthesis and chemical properties remain to be established.[1] In 1985, we suggested that the benzylic oxidation of 3-aryl-1-(trimethylsilyl)prop-1-yne with iodosylbenzene yielding an acetylenic ketone may involve formation of allenyliodinanes as intermediates.[2] We report herein evidence for the generation of hypervalent allenyl(aryl)iodinanes **2** by the reaction of propargylsilanes, germanes, and stannanes **1** with aryliodinanes. Furthermore, we disclose that the allenyliodinanes **2** undergo a novel type of Claisen rearrangement, termed a reductive iodonio-Claisen rearrangement, yielding *o*-propargyliodoarenes (Scheme I).

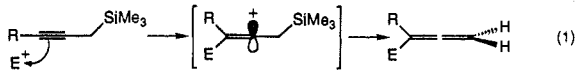
The results of reductive propargylation of aryliodinanes are summarized in Table I. Reaction of (diacetoxyiodo)benzene with 1,3-bis(trimethylsilyl)propyne (**1b**) is representative (entry 16): when (diacetoxyiodo)benzene was treated with 1.2 equiv of **1b** in the presence of BF_3–Et_2O (1 equiv) and $MgSO_4$ in dichloromethane at −20 °C for 1 h, 2-[3-(trimethylsilyl)-2-propynyl]-iodobenzene (**4b**) was obtained in 82% yield.[3] A variety of aryliodinanes including iodosylarenes, (diacetoxyiodo)arenes,[5] 1-hydroxy-1,2-benziodoxol-3(1*H*)-one, and hydroxy(tosyloxy)-iodobenzene undergo the reductive propargylation. Several characteristic features have been noted. First, the reductive propargylation of aryliodinanes proceeds regioselectively at the ortho position. Analogously to the Claisen rearrangement of allyl 3-methylphenyl ether,[6] reaction of 3-methyl(diacetoxyiodo)benzene with **1b** afforded a mixture of regioisomers **7a** and **7b** in a ratio of 64:36 (entry 24). A second feature is that the carbon–carbon bond formation takes place at the propargylic carbon atom of **1**. Third, the propargylation always involves reduction of iodinanes to univalent iodides. Fourth, the reaction generally proceeds at low temperature (−20 °C). And, finally, propargylgermane **1g** and propargylstannane **1h** also undergo the reductive propargylation of aryliodinanes (entries 12, 21, and 22).

Scheme I



1a: M = $SiMe_3$, R = H **1b**: M = R = $SiMe_3$ **1c**: M = $SiMe_3$, R = n-C_5H_{11} **1d**: M = $SiMe_3$, R = n-C_8H_{17} **1e**: M = $SiMe_3$, R= t-Bu **1f**: M = $SiMe_3$, R = cyclo-C_6H_{11} **1g**: M = $GePh_3$, R = H **1h**: M = $SnPh_3$, R = H

It has been well established that the reaction of propargylsilanes with electrophiles, such as halogens, acid chlorides, and carbocations, gives substituted allenes via an S_E2' process, which is facilitated by β-silicon stabilization of a cationic transition state (eq 1).[7] Thus, the reductive ortho propargylation of aryliodinanes



(1)

probably involves the intermediate formation of the allenyl(aryl)iodinanes **2**, produced by electrophilic attack of the positively charged iodine of aryliodinanes activated by the coordination of BF_3 to the oxygen atoms. Subsequent [3,3]-sigmatropic rearrangement of **2** providing **3**,[8,9] followed by the reductive elimination of acetic acid, may explain the formation of the *o*-propargyliodoarenes.

Reaction of 1-alkynyltrimethylsilanes with a combination of iodosylbenzene and BF_3–Et_2O in dichloromethane affords alky-

(1) For reviews of organoiodinanes, see: (a) Banks, D. F. *Chem. Rev.* **1966**, *66*, 243. (b) Koser, G. F. *The Chemistry of Functional Groups, Supplement D*; Wiley: New York, 1983; Chapter 18. (c) Varvoglis, A. *Synthesis* **1984**, 709. (d) Ochiai, M.; Nagao, Y. *J. Synth. Org. Chem., Jpn.* **1986**, *44*, 660. (e) Moriarty, R. M.; Prakash, O. *Acc. Chem. Res.* **1986**, *19*, 244. (f) Merkushev, E. B. *Russ. Chem. Rev.* **1987**, *56*, 826. (g) Ochiai, M. *Rev. Heteroatom Chem.* **1989**, *2*, 92. (h) Moriarty, R. M.; Vaid, R. K. *Synthesis* **1990**, 431. (i) Moriarty, R. M.; Vaid, R. K.; Koser, G. F. *Synlett* **1990**, 365.

(2) Ochiai, M.; Kunishima, M.; Sumi, K.; Nagao, Y.; Fujita, E.; Arimoto, M.; Yamaguchi, H. *Tetrahedron Lett.* **1985**, *26*, 4501.

(3) BF_3–Et_2O was used for activation of the aryliodinanes by coordination to the oxygen atoms.[4] Reaction of hydroxy(tosyloxy)iodobenzene with **1a**, however, proceeded at 0 °C without the catalyst to give **4a** (entry 27).

(4) (a) Ochiai, M.; Fujita, E.; Arimoto, M.; Yamaguchi, H. *J. Chem. Soc., Chem. Commun.* **1982**, 1108. (b) Ochiai, M.; Fujita, E.; Arimoto, M.; Yamaguchi, H. *Tetrahedron Lett.* **1983**, *24*, 777.

(5) (Diacetoxyiodo)arenes were prepared by sodium perborate oxidation of iodoarenes: McKillop, A.; Kemp, D. *Tetrahedron* **1989**, *45*, 3299.

(6) Tarbell, D. S.; Stradling, S. S. *J. Org. Chem.* **1962**, *27*, 2724.

(7) (a) Bourgeois, P.; Merault, G. *J. Organomet. Chem.* **1972**, *39*, C44. (b) Flood, T.; Peterson, P. E. *J. Org. Chem.* **1980**, *45*, 5006. (c) Despo, A. D.; Chiu, S. K.; Flood, T.; Peterson, P. E. *J. Am. Chem. Soc.* **1980**, *102*, 5120. (d) Schmid, R.; Huesmann, P. L.; Johnson, W. S. *J. Am. Chem. Soc.* **1980**, *102*, 5122. (e) Pornet, J. *Tetrahedron Lett.* **1981**, *22*, 453. (f) Pillot, J.-P.; Bennetau, B.; Dunogues, J.; Calas, R. *Tetrahedron Lett.* **1981**, *22*, 3401. (g) Bennetau, B.; Pillot, J.-P.; Dunogues, J.; Calas, R. *J. Chem. Soc., Chem. Commun.* **1981**, 1094. (h) Pornet, J.; Randrianoelina, B.; Miginiac, L. *Tetrahedron Lett.* **1984**, *25*, 651. (i) Klaver, W. J.; Hiemstra, H.; Speckamp, W. N. *Tetrahedron* **1988**, *44*, 6729.

(8) For Claisen rearrangement of allenyl ethers and sulfides, see: (a) Schuijl, P. J. W.; Brandsma, L. *Recl. Trav. Chim. Pays-Bas* **1969**, *88*, 1201. (b) Kwart, H.; George, T. J. *J. Chem. Soc., Chem. Commun.* **1970**, 433. (c) Krapf, M.; Dreiding, A. S. *Helv. Chim. Acta* **1977**, *60*, 3045.

(9) Allylic iodoso compounds undergo [2,3]-sigmatropic rearrangement: Yamamoto, S.; Itani, H.; Tsuji, T.; Nagata, W. *J. Am. Chem. Soc.* **1983**, *105*, 2908.

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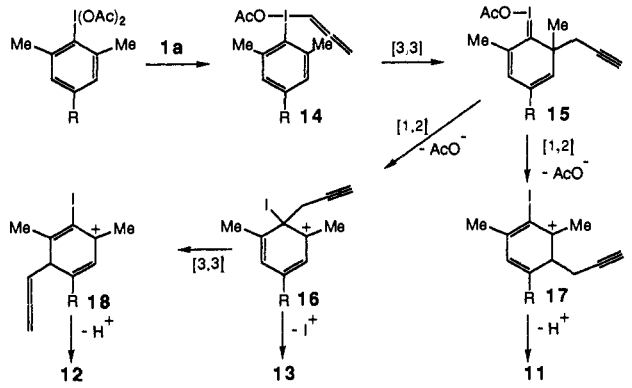
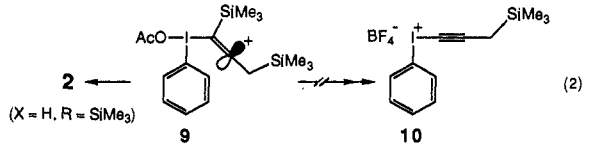
Scheme II



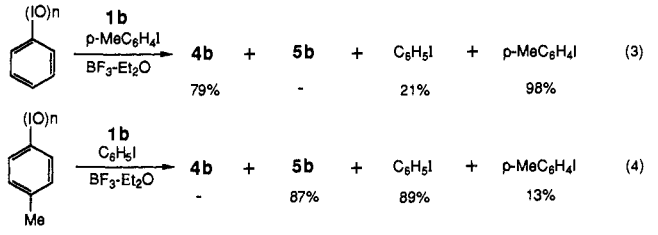
nyl(phenyl)iodonium tetrafluoroborates in good yield.[10] However, in the reaction of **1b** with iodosylbenzene or (diacetoxyiodo)-benzene in the presence of BF_3–Et_2O, the formation of 3-(trimethylsilyl)-1-propynyl(phenyl)iodonium tetrafluoroborate (**10**) was not detected (entries 7 and 16), which shows preferential loss of the allylic trimethylsilyl group from an intermediate vinyl cation **9** (eq 2). These results are consistent with the previous obser-



(2)

vations that in the reaction of **1b** with electrophilic reagents cleavage occurs at the silicon–propargylic carbon bond with rearrangement to an allene.[7a]

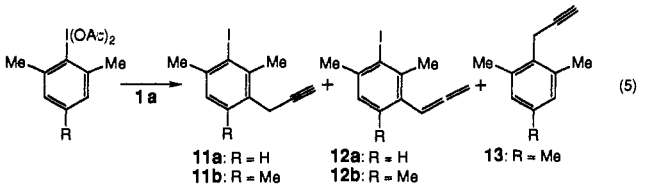
The lack of crossover products argues for the intramolecularity of the rearrangement of **2**. The reaction of iodosylbenzene with **1b** in the presence of 1 equiv of *p*-methyliodobenzene (−20 °C, 1 h) afforded the alkyne **4b** in good yield, and the formation of **5b** was not detected by GC analysis. *p*-Methyliodobenzene was recovered quantitatively (eq 3). Similar results were obtained from the reaction of 4-methyliodosylbenzene with **1b** in the presence of 1 equiv of iodobenzene (eq 4). These results combined with



the regioselective ortho propargylation make the ionic or radical dissociation–recombination mechanism for the rearrangement of **2** very unlikely. This is also supported by the fact that the reaction is relatively insensitive to solvent changes. Even in methanol, 2-(2-propynyl)iodobenzene (**4a**) was obtained in 62% yield by the reaction of iodosylbenzene with **1a** (entry 3).

[3,3]-Sigmatropic rearrangement of **2** takes place under much milder conditions than the Claisen rearrangement and its nitrogen and sulfur variants, which usually require heating at about 150–250 °C.[11-13] The lower activation energy associated with the iodonio-Claisen rearrangement of **2** can be interpreted in terms of the small bond energy needed to break the apical carbon–iodine(III) bond. In general, aryliodinanes $ArIX_2$ adopt a T-shaped geometry, the hypervalent I(III)–X bonds being well overlapped with the aromatic π bond.[1] This favorable orbital interaction could facilitate the rearrangement of **2**.

When both ortho positions of aryliodinanes were occupied with alkyl substituents, reductive iodonio rearrangement leading to the formation of meta and ipso substitution products were observed (eq 5). Although a free para position is available, the reaction



(5)

of 2,6-dimethyl(diacetoxyiodo)benzene with **1a** gave *m*-propargyliodobenzene **11a** (47%) and *m*-allenyliodobenzene **12a** (30%). With 2,4,6-trimethyl(diacetoxyiodo)benzene, the meta products **11b** (21%) and **12b** (37%) were obtained together with the ipso-substituted alkyne **13** (25%). These observations are in marked contrast to the results of Claisen rearrangement of ortho-disubstituted phenyl allyl ethers, which yield *p*-allylphenols through a subsequent Cope rearrangement.[14,15] The reaction of 2,6-dimethyl(diacetoxyiodo)benzene is the first to show that meta-Claisen rearrangement occurs preferentially even when a free para position is available.[16]

The formation of products **11–13** can be rationalized in terms of the facile 1,2-rearrangement of the propargyl group of **15**. The 1,2-rearrangement should be a low-energy process, because it involves a preferable reduction of trivalent iodine to univalent iodine (Scheme II). 1,2-Rearrangement to the meta position, followed by a deprotonation step, gives **11**. On the other hand, 1,2-rearrangement to the ipso position yielding **16** and the subsequent Cope rearrangement afford **12**. Deiodination of **16** gives rise to the ipso-substituted product **13**.[17] The presence of the *p*-methyl group in **15** seems to decrease the rate of 1,2-rearrangement of the propargyl group to the meta position compared with that to the ipso position, mostly due to steric and electronic[18] reasons. Similarly, the *p*-methyl group in **16** increases the energy requirement for the Cope rearrangement and, thus, the reaction accompanies the formation of **13**.

Conclusions. Although the intermediate allenyl(aryl)iodinanes have not been isolated and detected by NMR experiments, our results clearly indicate the in situ generation of the hitherto unknown allenyl(aryl)iodinanes by the reaction of propargylsilanes, germanes, and stannanes with aryliodinanes. The allenyl(aryl)-iodinanes undergo a reductive iodonio-Claisen rearrangement at low temperature, yielding *o*-propargyliodoarenes. Claisen rear-

(10) (a) Ochiai, M.; Kunishima, M.; Sumi, K.; Nagao, Y.; Fujita, E.; Arimoto, M.; Yamaguchi, H. *Tetrahedron Lett.* **1985**, *26*, 4501. (b) Kitamura, T.; Stang, P. J. *J. Org. Chem.* **1988**, *53*, 4105.

(11) (a) Rhoads, S. J. *Molecular Rearrangements*; de Mayo, P., Ed.; Interscience: New York, 1963; Vol. 1, pp 655–684. (b) Rhoads, S. J.; Raulins, N. R. *Org. React. (N. Y.)* **1975**, *22*, 1. (c) Tarbell, D. S. *Org. React. (N. Y.)* **1944**, *2*, 2. (d) Lutz, R. P. *Chem. Rev.* **1984**, *84*, 205. (e) Ziegler, F. E. *Chem. Rev.* **1988**, *88*, 1423.

(12) For amino-Claisen rearrangements, see: (a) Katayama, H. *Chem. Pharm. Bull.* **1978**, *26*, 2027. (b) Coats, R. M.; Said, I. M. *J. Am. Chem. Soc.* **1977**, *99*, 2355. (c) Inoue, S.; Takamatsu, N.; Kishi, Y. *Yakugaku Zasshi* **1977**, *97*, 553.

(13) Thio-Claisen rearrangements of dimethylallyl sulfonium salts have been reported to proceed at room temperature; Bycroft, B. W.; Landon, W. *J. Chem. Soc., Chem. Commun.* **1970**, 967.

(14) (a) Tarbell, D. S.; Kincaid, J. F. *J. Am. Chem. Soc.* **1940**, *62*, 728. (b) Pearl, I. A. *J. Am. Chem. Soc.* **1948**, *70*, 1746. (c) Curtin, D. Y.; Johnson, H. W. *J. Am. Chem. Soc.* **1956**, *78*, 2611. (d) Schmid, M.; Hansen, H.-J.; Schmid, H. *Helv. Chim. Acta* **1973**, *56*, 105. (e) Katayama, H.; Ohkoshi, M.; Kaneko, K. *Chem. Pharm. Bull.* **1984**, *32*, 1770.

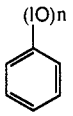
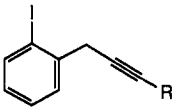
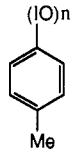
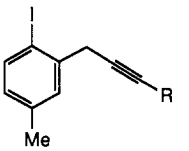
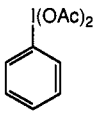
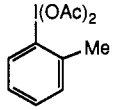
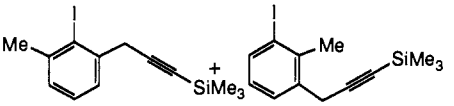
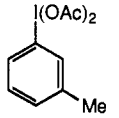
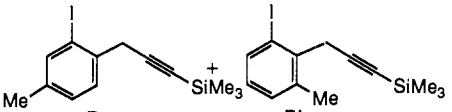
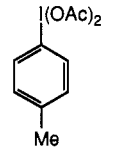
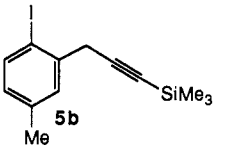
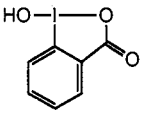
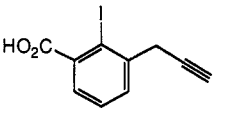
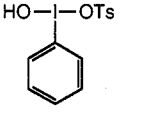
(15) Cope rearrangement of 1,5-hexenynes has been shown to proceed readily.[11b]

(16) A few meta-Claisen rearrangements were observed only when both ortho and para positions were occupied: (a) Katayama, H. *J. Chem. Soc., Chem. Commun.* **1980**, 1009. (b) Fahrni, P.; Habich, A.; Schmid, H. *Helv. Chim. Acta* **1960**, *43*, 448.

(17) In Claisen rearrangement, a displacement of chlorine and bromine atoms at ortho sites by allyl groups has been observed: (a) Hurd, C. D.; Webb, C. N. *J. Am. Chem. Soc.* **1936**, *58*, 2190. (b) Tarbell, D. S.; Wilson, J. W. *J. Am. Chem. Soc.* **1942**, *64*, 1066.

(18) Hyperconjugation by the *p*-methyl group will more efficiently stabilize the transition state leading to the carbocation **16** than that leading to **17**: (a) Kaneko, K.; Katayama, H.; Saito, Y.; Fujita, N.; Kato, A. *J. Chem. Soc., Chem. Commun.* **1986**, 1308. (b) Kruse, L. I.; Cha, J. K. *J. Chem. Soc., Chem. Commun.* **1982**, 1333.

Table I. Reductive Iodonio-Claisen Rearrangement[a]

entry	aryliodinane	1 (equiv)	temp, °C (time, h)	additive	solvent	product(s)	%yield[b] (ratio)
							
1		**1a** (2.0)	-20 (1)	$MgSO_4$	CH_2Cl_2	**4a** R = H	80
2		**1a** (2.0)	-20 (1)	—	CH_2Cl_2	**4a**	75
3		**1a** (2.0)	-20 (1)	$MgSO_4$	MeOH	**4a**	62
4		**1a** (2.0)	-20 (1)	$MgSO_4$	CCl_4	**4a**	60
5		**1a** (2.0)	-20 (1)	$MgSO_4$	hexane	**4a**	49
6		**1a** (2.0)	-20 (1)	$MgSO_4$	Et_2O	**4a**	77
7		**1b** (1.2)	-20 (1)	$MgSO_4$	CH_2Cl_2	**4b** R = $SiMe_3$	67
8		**1c** (1.2)	-20 (1)	$MgSO_4$	CH_2Cl_2	**4c** R = n-C_5H_{11}	85
9		**1d** (1.2)	-20 (1)	$MgSO_4$	CH_2Cl_2	**4d** R = n-C_8H_{17}	96
10		**1e** (1.5)	-20 (1)	$MgSO_4$	CH_2Cl_2	**4e** R = t-Bu	64
11		**1f** (1.2)	-20 (1)	$MgSO_4$	CH_2Cl_2	**4f** R = cyclo-C_6H_{11}	65
12		**1g** (1.3)	-20 (1)	$MgSO_4$	CH_2Cl_2	**4a**	76
							
13		**1a** (2.0)	-20 (1)	$MgSO_4$	CH_2Cl_2	**5a** R = H	73
14		**1b** (1.2)	-20 (1)	$MgSO_4$	CH_2Cl_2	**5b** R = $SiMe_3$	86
							
15		**1a** (2.0)	-20 (1)	$MgSO_4$	CH_2Cl_2	**4a**	66
16		**1b** (1.2)	-20 (1)	$MgSO_4$	CH_2Cl_2	**4b**	82
17		**1c** (1.2)	-20 (1)	$MgSO_4$	CH_2Cl_2	**4c**	80
18		**1d** (1.2)	-30 (1)	$MgSO_4$	CH_2Cl_2	**4d**	88
19		**1e** (1.5)	-20 (1)	$MgSO_4$	CH_2Cl_2	**4e**	51
20		**1f** (1.2)	-20 (1)	$MgSO_4$	CH_2Cl_2	**4f**	90
21		**1g** (1.2)	-20 (1)	$MgSO_4$	CH_2Cl_2	**4a**	85
22		**1h** (1.1)	-20 (1)	$MgSO_4$	CH_2Cl_2	**4a**	51
23		**1b** (1.2)	-20 (1)	$MgSO_4$	CH_2Cl_2	 **6a** **6b**	84 (91:9)
24		**1b** (1.2)	-20 (1)	$MgSO_4$	CH_2Cl_2	 **7a** **7b**	91 (64:36)
25		**1b** (1.2)	-20 (1)	$MgSO_4$	CH_2Cl_2	 **5b**	71
26		**1a** (2.0)	25 (1.5)	—	CH_2Cl_2	 **8**	46[c]
27		**1a**[d] (2.0)	0 (3)	—	CH_2Cl_2	**4a**	41

[a] BF_3-Et_2O (1 equiv) was used unless otherwise noted. [b] Isolated yields of products. [c] Yields were determined by ^1H NMR. [d] Reactions were performed without BF_3-Et_2O.

rangements involving oxygen, nitrogen, sulfur, and phosphorus[19] atoms of groups 15 and 16 have well precedented; however, Claisen rearrangement involving atoms of group 17 has never been reported. The reaction is very useful for introducing propargyl groups at the ortho sites of iodoarenes.

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Experimental Section

General Information. IR spectra were recorded on a Jasco IRA-1 spectrometer. ^1H and ^{13}C NMR were recorded in $CDCl_3$ on a JEOL

JNM-GX 270 spectrometer. Chemical shifts were reported in parts per million (ppm) downfield from internal Me_4Si. Mass spectra (MS) were obtained on a JMS-D300 spectrometer. Melting points were determined with a Yanaco micro melting point apparatus and are uncorrected.

Reactions were performed under a nitrogen atmosphere. THF was distilled from sodium benzophenone ketyl under nitrogen. Dichloromethane was dried over CaH_2 and distilled. BF_3–Et_2O was distilled from CaH_2 under nitrogen. Analytical gas chromatography (GC) was carried out on a Shimadzu GC-8A gas chromatograph with a column of 20% silicone SF-96 on Chromosorb W. Thin-layer chromatography (TLC) was carried out on Kieselgel 60 F_{254} (Merck).

Propargylsilanes, germanes, and stannanes were prepared according to literature procedure: 1-(trimethylsilyl)-2-propyne (**1a**),[20] 1,3-bis(trimethylsilyl)propyne (**1b**),[21] 1-(trimethylsilyl)-2-octyne (**1c**),[22] 1-(trimethylsilyl)-2-undecyne (**1d**),[23] 4,4-dimethyl-1-(trimethylsilyl)-2-pentyne (**1e**),[22] [3-(trimethylsilyl)-1-propynyl]cyclohexane (**1f**),[22] 1-(triphenylgermyl)-2-propyne (**1g**),[24] 1-(triphenylstannyl)-2-propyne (**1h**).[25] (Diacetoxyiodo)benzene was synthesized by peracetic acid oxidation of iodobenzene.[26] 2-Methyl-, 3-methyl-, 4-methyl-, 2,6-dimethyl-, and 2,4,6-trimethyl(diacetoxyiodo)benzene were prepared as previously described.[5] Iodosylbenzene and *p*-iodosyltoluene were prepared by the hydrolysis of the corresponding diacetates with aqueous sodium hydroxide.[27] 1-Hydroxy-1,2-benziodoxol-3(1*H*)-one and hydroxy(tosyloxy)iodobenzene were obtained from commercial sources and were used without further purification.

General Procedure for the Reductive Propargylation of Aryliodinanes. In a 20-mL oven-dried two-necked round-bottomed flask fitted with a nitrogen balloon, a rubber septum, and a magnetic stirring bar were placed an aryliodinane (0.3 mmol), a propargylsilane, anhydrous $MgSO_4$ (100 mg), which was dried at 100 °C for 3 h under vacuum, and 2 mL of freshly distilled dichloromethane. The reaction flask was cooled to −20 °C (dry ice/carbon tetrachloride bath), and 0.037 mL (0.3 mmol) of freshly distilled BF_3–Et_2O was added dropwise. The reaction mixture was stirred under the conditions described in Table I. The mixture was quenched by addition of water and extracted with hexane. The combined organic extracts were washed with brine, dried over anhydrous Na_2SO_4, and filtered. Concentration in vacuo gave an oil, which was purified by preparative TLC [hexane or hexane–ethyl acetate (8:2)]. The yields of pure products are given in Table I.

1-(2-Iodophenyl)-2-propyne (4a): IR ($CHCl_3$) 3300, 2120, 1580, 1565, 1460, 1430, 1005 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.82 (dd, J = 7.8, 1.0 Hz, 1 H), 7.61 (dd, J = 7.8, 1.7 Hz, 1 H), 7.34 (dt, J = 1.0, 7.8 Hz, 1 H), 6.94 (dt, J = 1.7, 7.8 Hz, 1 H), 3.63 (d, J = 2.8 Hz, 2 H), 2.27 (t, J = 2.8 Hz, 1 H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 139.3, 138.7, 129.0, 128.6, 128.5, 99.7, 81.1, 71.7, 31.1; MS m/z (relative intensity) 242 (84, M^+), 115 (100). HRMS Calcd for C_9H_7I (M^+): 241.9595. Found: 241.9603.

1-(2-Iodophenyl)-3-(trimethylsilyl)-2-propyne (4b): IR ($CHCl_3$) 3300, 2970, 2170, 1580, 1560, 1460, 1430, 1310, 1220, 1010, 845 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.82 (br d, J = 7.7 Hz, 1 H), 7.62 (br d, J = 7.7 Hz, 1 H), 7.36 (br t, J = 7.7 Hz, 1 H), 6.95 (br t, J = 7.7 Hz, 1 H), 3.68 (s, 2 H), 0.22 (s, 9 H); MS m/z (relative intensity) 314 (44, M^+), 299 (100), 172 (24), 129 (25). HRMS Calcd for $C_{12}H_{15}ISi$ (M^+): 313.9990. Found: 314.0000.

1-(2-Iodophenyl)-2-octyne (4c): IR ($CHCl_3$) 2960, 2200, 1580, 1560, 1460, 1010, 850 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.81 (dd, J = 7.8, 1.0 Hz, 1 H), 7.62 (dd, J = 7.8, 1.0 Hz, 1 H), 7.35 (dt, J = 1.0, 7.8 Hz, 1 H), 6.94 (dt, J = 1.0, 7.8 Hz, 1 H), 3.60 (t, J = 2.2 Hz, 2 H), 2.28–2.21 (m, 2 H), 1.62–1.49 (m, 2 H), 1.49–1.26 (m, 4 H), 0.92 (t, J = 6.8 Hz, 3 H); MS m/z (relative intensity) 312 (3, M^+), 255 (8), 230 (21), 217 (14), 129 (78), 95 (100). HRMS Calcd for $C_{14}H_{17}I$ (M^+): 312.0376. Found: 312.0356.

1-(2-Iodophenyl)-2-undecyne (4d): IR ($CHCl_3$) 2930, 2160, 1585, 1560, 1460, 1435, 1245, 1010, 850 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.81 (dd, J = 7.8, 1.0 Hz, 1 H), 7.61 (br d, J = 7.8 Hz, 1 H), 7.34 (dt, J = 1.0, 7.8 Hz, 1 H), 6.93 (dt, J = 1.0, 7.8 Hz, 1 H), 3.59 (t, J = 2.0 Hz, 2 H), 2.28–2.19 (m, 2 H), 1.62–1.20 (12 H), 0.89 (t, J = 6.8 Hz, 3 H); MS m/z (relative intensity) 354 (3, M^+), 217 (40), 170 (22), 137 (60), 129 (98), 81 (100). HRMS Calcd for $C_{17}H_{23}I$ (M^+): 354.0847. Found: 354.0863.

4,4-Dimethyl-1-(2-iodophenyl)-2-pentyne (4e): IR ($CHCl_3$) 2960, 1560, 1455, 1430, 1310, 1260, 1010 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.81 (dd, J = 7.9, 1.0 Hz, 1 H), 7.61 (dd, J = 7.9, 1.0 Hz, 1 H), 7.35 (dt, J = 1.0, 7.9 Hz, 1 H), 6.94 (dt, J = 1.0, 7.9 Hz, 1 H), 3.58 (s, 2 H), 1.27 (s, 9 H); MS m/z (relative intensity) 298 (93, M^+), 255 (69), 156 (100), 141 (66), 128 (37), 115 (31). HRMS Calcd for $C_{13}H_{15}I$ (M^+): 298.0221. Found: 298.0234.

[3-(2-Iodophenyl)-1-propynyl]cyclohexane (4f): IR ($CHCl_3$) 2940, 2200, 1580, 1560, 1460, 1440, 1010, 890, 850 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.81 (dd, J = 7.8, 1.0 Hz, 1 H), 7.63 (br d, J = 7.8 Hz, 1 H), 7.34 (dt, J = 1.0, 7.8 Hz, 1 H), 6.93 (dt, J = 1.0, 7.8 Hz, 1 H), 3.61 (d, J = 2.0 Hz, 2 H), 2.52–2.35 (m, 1 H), 1.92–1.63 (m, 4 H), 1.63–1.17 (m, 6 H); MS m/z (relative intensity) 324 (100, M^+), 282 (9), 255 (10), 232 (11), 217 (18), 155 (40), 141 (43), 129 (42), 115 (44), 107 (32). HRMS Calcd for $C_{15}H_{17}I$ (M^+): 324.0376. Found: 324.0372.

1-(2-Iodo-5-methylphenyl)-2-propyne (5a): IR ($CHCl_3$) 3300, 2920, 2200, 2120, 1590, 1460, 1010, 870 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.67 (d, J = 7.8 Hz, 1 H), 7.41 (br s, 1 H), 6.77 (dd, J = 7.8, 1.5 Hz, 1 H), 3.60 (d, J = 2.8 Hz, 2 H), 2.31 (s, 3 H), 2.27 (t, J = 2.8 Hz, 1 H); MS m/z (relative intensity) 256 (98, M^+), 129 (100). HRMS Calcd for $C_{10}H_9I$ (M^+): 255.9752. Found: 255.9773.

1-(2-Iodo-5-methylphenyl)-3-(trimethylsilyl)-2-propyne (5b): IR ($CHCl_3$) 2960, 2180, 1590, 1460, 1220, 1010, 850 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.67 (d, J = 7.8 Hz, 1 H), 7.42 (br s, 1 H), 6.78 (dd, J = 7.8, 1.0 Hz, 1 H), 3.64 (s, 2 H), 2.33 (s, 3 H), 0.23 (s, 9 H); MS m/z (relative intensity) 328 (57, M^+), 313 (100), 186 (38), 171 (19), 143 (50). HRMS Calcd for $C_{13}H_{17}ISi$ (M^+): 328.0146. Found: 328.0126.

1-(2-Iodo-3-methylphenyl)-3-(trimethylsilyl)-2-propyne (6a): IR ($CHCl_3$) 2960, 2165, 1570, 1455, 1400, 1295, 1220, 1140, 1000, 895, 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.44 (br d, J = 7.3 Hz, 1 H), 7.24 (t, J = 7.3 Hz, 1 H), 7.14 (br d, J = 7.3 Hz, 1 H), 3.73 (s, 2 H), 2.49 (s, 3 H), 0.22 (s, 9 H); MS m/z (relative intensity) 328 (70, M^+), 313 (100), 186 (29), 171 (37), 143 (57), 128 (19). HRMS Calcd for $C_{13}H_{17}ISi$ (M^+) 328.0146. Found: 328.0134.

1-(3-Iodo-2-methylphenyl)-3-(trimethylsilyl)-2-propyne (6b): IR ($CHCl_3$) 3000, 2960, 2160, 1560, 1430, 1245, 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.75 (d, J = 7.8 Hz, 1 H), 7.40 (d, J = 7.8 Hz, 1 H), 6.86 (t, J = 7.8 Hz, 1 H), 3.61 (s, 2 H), 2.45 (s, 3 H), 0.17 (s, 9 H); MS m/z (relative intensity) 328 (28, M^+), 313 (59), 254 (14), 201 (11), 186 (19), 171 (23), 156 (10), 143 (10), 128 (26), 73 (100). HRMS Calcd for $C_{13}H_{17}ISi$ (M^+): 328.0146. Found: 328.0131.

1-(2-Iodo-4-methylphenyl)-3-(trimethylsilyl)-2-propyne (7a): IR ($CHCl_3$) 2965, 2165, 1600, 1475, 1400, 1240, 1120, 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.65 (br s, 1 H), 7.47 (d, J = 7.8 Hz, 1 H), 7.15 (br d, J = 7.8 Hz, 1 H), 3.63 (s, 2 H), 2.29 (s, 3 H), 0.20 (s, 9 H); MS m/z (relative intensity) 328 (42, M^+), 313 (100), 201 (11), 186 (44), 171 (20), 143 (44). HRMS Calcd for $C_{13}H_{17}ISi$ (M^+): 328.0146. Found: 328.0128.

1-(2-Iodo-6-methylphenyl)-3-(trimethylsilyl)-2-propyne (7b): IR ($CHCl_3$) 2960, 2165, 1555, 1440, 1240, 1105, 1015, 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.70 (br d, J = 7.8 Hz, 1 H), 7.14 (br d, J = 7.8 Hz, 1 H), 6.83 (t, J = 7.8 Hz, 1 H), 3.78 (s, 2 H), 2.48 (s, 3 H), 0.13 (s, 9 H); MS m/z (relative intensity) 328 (36, M^+), 313 (100), 201 (13), 186 (69), 171 (26), 143 (74). HRMS Calcd for $C_{13}H_{17}ISi$ (M^+): 328.0146. Found: 328.0165.

2-Iodo-3-(2-propynyl)benzoic acid (8): mp 175–177 °C (recrystallized from chloroform); IR (KBr) 3285, 3100–2980, 1675, 1415, 1280, 1160, 1015, 745 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.81 (br d, J = 7.8 Hz, 1 H), 7.68 (br d, J = 7.8 Hz, 1 H), 7.42 (t, J = 7.8 Hz, 1 H), 3.78 (d, J = 2.6 Hz, 2 H), 2.33 (t, J = 2.6 Hz, 1 H); MS m/z (relative intensity) 286 (100, M^+), 268 (20), 159 (66), 114 (44), 113 (44), 103 (51). HRMS Calcd for $C_{10}H_7IO_2$ (M^+): 285.9492. Found: 285.9482. Anal. Calcd for $C_{10}H_7IO_2$: C, 41.99; H, 2.47. Found: C, 41.70; H, 2.49.

Reaction of Iodosylbenzene with 1,3-Bis(trimethylsilyl)propyne (1b) in the Presence of *p*-Methyliodobenzene. The reaction was carried in the presence of *p*-methyliodobenzene (0.3 mmol) according to the general procedure (Table I, entry 7). Analytical GC showed the formation of **4b** (79%) and iodobenzene (21%). *p*-Methyliodobenzene was recovered in 98% yield, and **5b** was not detected by GC.

Reaction of *p*-Iodosyltoluene with 1,3-Bis(trimethylsilyl)propyne (1b) in the Presence of Iodobenzene. The reaction was carried in the presence of iodobenzene (0.3 mmol) according to the general procedure (Table I, entry 14). Analytical GC showed the formation of **5b** (87%) and *p*-methyliodobenzene (13%). Iodobenzene was recovered in 89% yield, and **4b** was not detected by GC.

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Reaction of 2,6-Dimethyl(diacetoxyiodo)benzene with Propargylsilane 1a. With use of the general procedure, reaction of 0.105 g (0.3 mmol) of 2,6-dimethyl(diacetoxyiodo)benzene with 0.084 g (0.6 mmol) of **1a** (80% purity) in the presence of 0.1 g of $MgSO_4$ and 0.043 g (0.3 mmol) of BF_3-Et_2O was carried out at -20 °C for 2 h. ^1H NMR of the crude product showed the formation of 1-(2,4-dimethyl-3-iodophenyl)-2-propyne (**11a**) (47%) and 1-(2,4-dimethyl-3-iodophenyl)-1,2-propadiene (**12a**) (30%). Preparative TLC afforded **11a** (33.8 mg, 42%) and **12a** (18.4 mg, 23%). **11a**: IR ($CHCl_3$) 3300, 2925, 2120, 1560, 1445, 1375, 1185, 990 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.27 (d, J = 7.8 Hz, 1 H), 7.06 (d, J = 7.8 Hz, 1 H), 3.57 (d, J = 2.6 Hz, 2 H), 2.52 (s, 3 H), 2.46 (s, 3 H), 2.18 (t, J = 2.6 Hz, 1 H); MS m/z (relative intensity) 270 (83, M^+), 143 (73), 128 (100), 115 (40). HRMS Calcd for $C_{11}H_{11}I$ (M^+): 269.9907. Found: 269.9898. **12a**: IR ($CHCl_3$) 2960, 2920, 1940, 1580, 1445, 1375, 1005, 990, 850 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.25 (d, J = 7.8 Hz, 1 H), 7.04 (d, J = 7.8 Hz, 1 H), 6.38 (t, J = 6.7 Hz, 1 H), 5.11 (d, J = 6.7 Hz, 2 H), 2.55 (s, 3 H), 2.45 (s, 3 H); MS m/z 270 (M^+). HRMS Calcd for $C_{11}H_{11}I$ (M^+): 269.9907. Found: 269.9921.

Reaction of 2,4,6-Trimethyl(diacetoxyiodo)benzene with Propargylsilane 1a. With use of the general procedure, reaction of 0.109 g (0.3 mmol) of 2,4,6-trimethyl(diacetoxyiodo)benzene with 0.084 g (0.6 mmol) of **1a** (80% purity) in the presence of 0.1 g of $MgSO_4$ and 0.043 g (0.3 mmol) of BF_3-Et_2O was carried out at -20 °C for 2 h. ^1H NMR of the crude product showed the formation of 1-(2,4,6-trimethyl-3-iodophenyl)-2-propyne (**11b**) (21%), 1-(2,4,6-trimethyl-3-iodophenyl)-1,2-propadiene (**12b**) (37%), and 1-(2,4,6-trimethylphenyl)-2-propyne (**13**)[28] (25%). The products were separated by preparative TLC. **11b**: IR ($CHCl_3$) 3300, 3005, 2110, 1445, 1375, 1260, 1135, 965, 860 cm^{-1}; ^1H NMR ($CDCl_3$) δ 6.96 (s, 1 H), 3.56 (d, J = 2.6 Hz, 2 H), 2.62 (s, 3 H), 2.42 (s, 3 H), 2.33 (s, 3 H), 1.98 (t, J = 2.6 Hz, 1 H); MS m/z (relative intensity) 284 (100, M^+), 157 (26), 142 (38). HRMS Calcd for $C_{12}H_{13}I$ (M^+): 284.0064. Found: 284.0079. **12b**: IR ($CHCl_3$) 2925, 1940, 1445, 1375, 1150, 965, 865, 845 cm^{-1}; ^1H NMR ($CDCl_3$) δ 6.96 (s, 1 H), 6.20 (t, J = 7.0 Hz, 1 H), 4.91 (d, J = 7.0 Hz, 2 H), 2.58 (s, 3 H), 2.42 (s, 3 H), 2.28 (s, 3 H); MS m/z (relative intensity) 284 (30, M^+), 256 (12), 157 (100), 132 (92), 128 (26), 115 (34). HRMS Calcd for $C_{12}H_{13}I$ (M^+): 284.0064. Found: 284.0054. **13**:[28] ^1H NMR ($CDCl_3$) δ 6.86 (s, 2 H), 3.46 (d, J = 2.8 Hz, 2 H), 2.37 (s, 6 H), 2.26 (s, 3 H), 1.95 (t, J = 2.8 Hz, 1 H). Deiodination of **11b** with butyllithium in THF at -78 °C for 2 h gave **13** in 71% yield.

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Syntheses and Properties of Highly Symmetrical Cage Compounds: Pyridine Analogues of Hexa-*m*-xylylenetetraamine

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Abstract: Syntheses and properties of pyridine analogues, **2**-**4**, of "Hexa-*m*-xylylenetetraamine", **1**, are discussed. The analogues containing four or six pyridine rings, **3** and **4**, serve as cryptands and generate stable, kinetically inert metal ion cryptates and proton cryptates. The proton cryptates could not be deprotonated even by strong bases. Ion-exchange resin treatment of the proton cryptates, $H^+\subset$**3**$\cdot NO_3^-$ and $H^+\subset$**4**$\cdot NO_3^-$, gave proton cryptates whose counter anion is a hydroxide ion. These compounds were gradually converted into water cryptates. The dynamic behavior of the proton cryptate, potassium cryptate, and water cryptate was studied by a temperature-dependent NMR method. The analogues containing two pyridine rings, **2**, and its derivatives, **2**-OMe and **2**-Cl, were synthesized. Their alkali metal ion selectivity and complexation ability were compared by alkali metal picrates extraction experiments to investigate the effect of the number of pyridine rings as well as the effect of the substituents on the complexation ability. Inversion of bridgehead nitrogens of **1** are restricted; this was supported by methylation or protonation experiments of the bridgehead nitrogens. Enantiomeric interconversion of methylene moieties around the bridgehead nitrogens was frozen at low temperatures; therefore, resolution of these enantiomers in ^1H NMR spectra was achieved by using the optically active reagent, (*S*)-(+)-2,2,2-trifluoro-1-(9-anthryl)ethanol.

Introduction

In recent years, the chemistry of macrocycles has been remarkably developed, and many studies on designing host molecules and[1,2] inclusion of ions and molecules[3-8] as well as the construction of reaction sites[9-11] have been reported. Guest recognition of the host molecule is determined by the cavity size, topology of the coordinating groups, and hydrophilicity or hydrophobicity of the cavity of the host molecules. Furthermore, guest binding is profitable when the host molecule is preorganized, and a host-guest complex is more stable when the cavity is isolated from the outside influences of the host molecule.

Therefore, we report the syntheses and properties of highly structured, preorganized cryptands, **1**-**4** (Figure 1). Each compound has a cavity which is isolated from the outside influences around the molecule. It is expected that shielding of the cavity by the thick aromatic walls of such compounds causes effective ion separation on complexation and that anion activation will be

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