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Iterative Dianion Relay Along the Ring: Formation of *gem*-Bis(trimethylsilyl) Cyclopentenones from 2,5-Bis(trimethylsilyl) Oxy-cyclopentadienyl Dianions and Acid Chlorides

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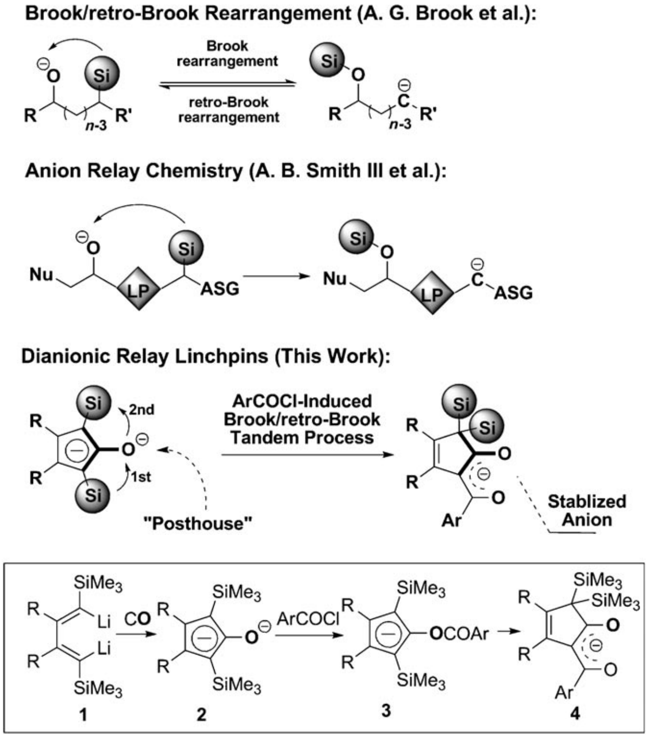
Anionic migration of silyl groups has become one of the most useful protocols for synthetic chemistry.[1–3] The intramolecular 1,*n*-anionic migration of a silyl group from a carbon atom to an oxygen atom is generally referred to as Brook rearrangement (Scheme 1) and the reverse process (from an oxygen atom to a carbon atom) is called retro-Brook rearrangement (or West rearrangement).[1,4–6] Both the Brook rearrangement and the retro-Brook rearrangement are currently widely applied in organic synthesis.[1,2] As illustrated in Scheme 1, a recent yet very useful strategy applying anionic migrations of silyl groups is the anion relay chemistry (ARC) developed by Smith III et al.[7f,g,h,j,k] The ARC, a multi-component linchpin protocol, has been demonstrated to be useful for high-efficient and facile synthesis of structurally complex scaffolds.[3] To further apply to synthetic chemistry the useful protocol based on the anionic migration of silyl groups, the design and development of new linchpins is currently of great demand and represents a great challenge. In recent years, we have demonstrated that the reaction of 1,4-dilithio-1,3-butadienes **1** with CO leads to the formation of substituted oxy-cyclopentadienyl dianion intermediates **2** (OCp dianions; Cp = cyclopentadienyl).[8] Because of the concomitance of the Cp anion, the exocyclic oxyanion, and those multi-reactive sites, the OCp dianions **2** are structurally very unique and can be used for novel reaction chemistry. During the course of our continuous study on their reaction chemistry, we realized that those OCp dianions substituted with trimethylsilyl groups could be used as a new type of dianionic relay linchpins. Iterative anion relay, in which one silyl group was shifted twice along the Cp ring with the exocyclic oxyanion as the posthouse, was observed the first time in anionic migration of silyl groups (Scheme 1). Interesting and otherwise unavailable compounds have been thus generated. Herein, we report our preliminary results.



Scheme 1. Modes of anionic migration of silyl groups. ASG = anion stabilizing group, LP = linchpin.

1,4-Dilithio-1,4-bis(trimethylsilyl)-1,3-butadienes (dilithio reagents) **1** can be readily generated in quantitative yields from their corresponding 1,4-diiodobutadienes and *t*BuLi.[8b] Treatment of dilithio reagents **1** with CO led to the formation of OCp dianions **2**. When the reaction mixture containing **2a** in diethyl ether was further treated with two equivalents of ArCOCl possessing electron-donating groups on Ar, such as 4-methylbenzoyl chloride, a double-acylation product was obtained.[8b] However, surprisingly, when one equivalent of PhCOCl was used, the 3-cyclopentenone derivative **5aa** containing a stable enol moiety was obtained in 74 %

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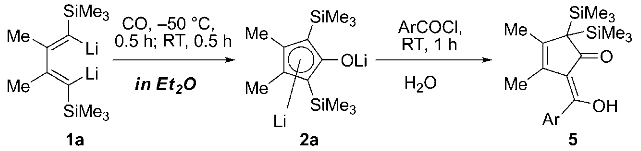
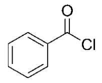
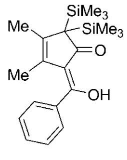
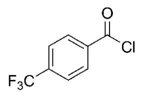
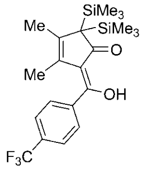
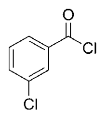
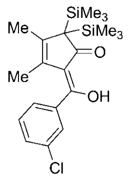
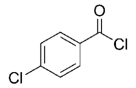
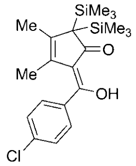
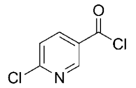
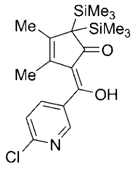
Table 1. Formation of *gem*-bis(trimethylsilyl) cyclopentenones containing a stable enol moiety from electron-withdrawing ArCOCl.



Entry	ArCOCl	Product	Yield [%][a]
1	 **7a**	 **5aa**	74
2	 **7b**	 **5ab**	80
3	 **7c**	 **5ac**	84
4	 **7d**	 **5ad**	65
5	 **7e**	 **5ae**	66

[a] Yield of isolated product.

yield of the isolated product upon hydrolysis of the reaction mixture (Table 1, entry 1). No double-acylation product was obtained even when two equivalents of PhCOCl were used. The X-ray structural analysis of **5aa** revealed clearly that two trimethylsilyl groups were attached on the same carbon atom (Figure 1). With this result in hand, we were curious about the influence of the electronic effect of the Ar group on this reaction. Thus, ArCOCl moieties containing electron-withdrawing groups were tested. Stable enol derivatives **5ab**–**5ae** as the sole products were obtained in good to excellent yields of the isolated product (Table 1, entries 2–5).

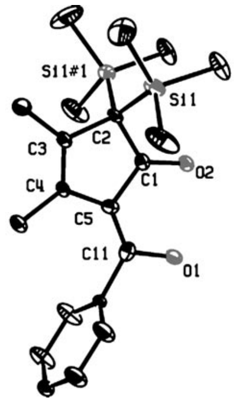


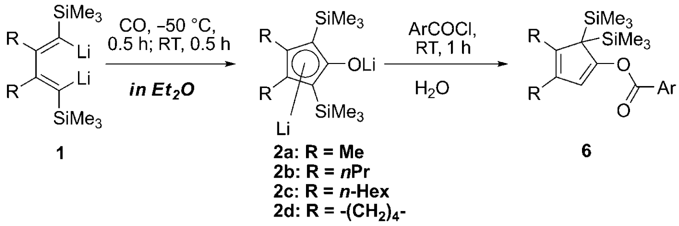
Figure 1. ORTEP drawing of **5aa** with 30% thermal ellipsoids. Hydrogen atoms are omitted for clarity. Selected bond lengths [Å]: C1–C2 1.498(7), C1–C5 1.474(6), C2–C3 1.550(6), C3–C4 1.324(6), C4–C5 1.451(6), C5–C11 1.339(6), C1–O2 1.271(5), C11–O1 1.364(5), C2–Si1 1.929(3), C2–Si1#1 1.929(3).

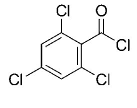
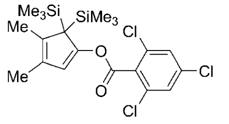
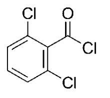
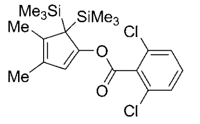
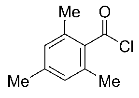
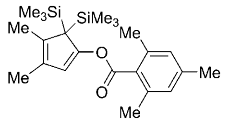
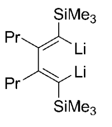
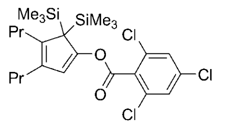
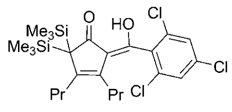
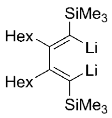
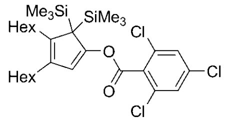
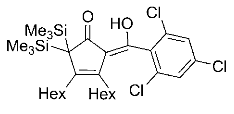
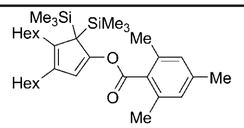
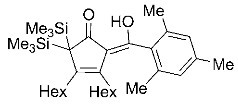
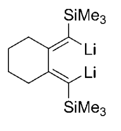
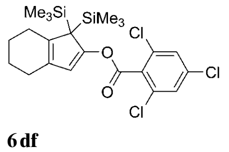
The skeleton of stable enols **5aa**–**5ae** represents a new type among the reported structures.[9] We believe that this transformation process is unprecedented and should be of mechanistic significance.

To obtain more evidence for the understanding of the reaction mechanism, we used more acid chlorides with diversified substituents on the Ar group. The results are listed in Table 2. When we used 2,4,6-trichlorobenzoyl chloride to react with **2a** in diethyl ether solvent, another unexpected type of product **6af** was obtained in 70% yield of the isolated product upon hydrolysis of the reaction mixture with water (Table 2, entry 1). This is a cyclopentadiene derivative, again with the shift of one $SiMe_3$ group. Obviously, this product is structurally very different from products **5**. We then used 2,4,6-trichlorobenzoyl chloride, 2,6-dichlorobenzoyl chloride and 2,4,6-trimethylbenzoyl chloride to react with **2a**–**2d**, respectively. The type **6** products were also obtained generally in good yields. The structure of **6ag** was confirmed by single crystal X-ray structural analysis (see the Supporting Information). It was interesting to observe the formation of by-products **5bf**, **5cf**, and **5ch** (Table 2, entries 4–6). With the enlargement of the alkyl group R, the yield of byproducts of the type **5** increased (Table 2, entries 1, 4, and 5). The different aggregation pattern among **2a** (Me), **2b** (*n*Pr), and **2c** (*n*-Hex) is proposed to be the major reason for such a difference.[10]

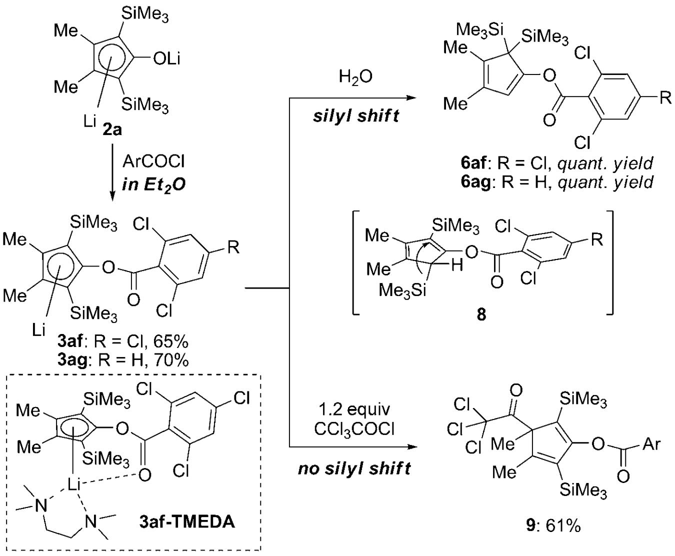
The above transformations leading to the type **5** products and the type **6** products were both intriguing. We set our mind on making clear this novel transformation by isolating the intermediates. First, we successfully isolated the intermediates from the reaction mixture between the OCp dianions **2** with acid chlorides. As given in Scheme 2, when the OCp dianion **2a** was treated with 2,4,6-trichlorobenzoyl chloride, the *O*-acylated intermediate **3af** was obtained in 65% yield of the isolated product. In a similar manner, **3ag** was obtained in 70% yield of the isolated product.

Table 2. Formation of *gem*-bis(trimethylsilyl) cyclopentadienes from bulky ArCOCl.



Entry	Dilithio reagent	ArCOCl	Product	Yield [%][a]
1	**1a**	 **7f**	 **6af**	70
2	**1a**	 **7g**	 **6ag**	77
3	**1a**	 **7h**	 **6ah**	77
4	 **1b**	**7f**	 **6bf**	62
			 **5bf**	12
5	 **1c**	**7f**	 **6cf**	43
			 **5cf**	26
6	**1c**	**7h**	 **6ch**	48
			 **5ch**	22
7	 **1d**	**7f**	 **6df**	62

[a] Yield of isolated product.



Scheme 2. Isolation and trapping experiments of the O-acylated intermediates. Ar = 2,4,6-trichlorophenyl.

Recrystallization of **3af** with 1 equivalent of *N*,*N*,*N*′,*N*′-tetramethylethylenediamine (TMEDA) from Et_2O/hexane (1:1) mixed solvent afforded the single crystals **3af-TMEDA**, whose structure was successfully determined by single-crystal X-ray structural analysis (Figure 2). The structure of **3af-TMEDA** is a monomeric CpLi compound in which the distances between the lithium and the carbons of Cp ring range from 2.352 Å to 2.588 Å.[11] The Li1–C1 bond length (2.352 Å) is significantly shorter than Li1-C2-5 (2.455-2.588 Å), owing to the coordination of the oxygen in the carbonyl group. Hydrolysis of the isolated intermediates **3af** and **3ag** with water afforded their corresponding product **6af** and **6ag** in quantitative yields. These results demonstrated that compounds **6** must be formed upon protonation

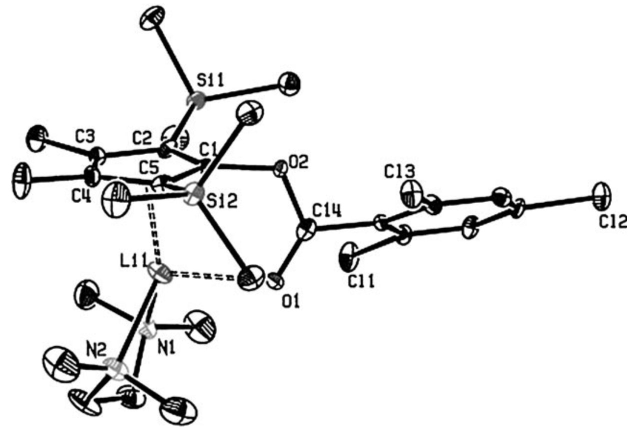


Figure 2. ORTEP drawing of **3af-TMEDA** with 30 % thermal ellipsoids. Hydrogen atoms are omitted for clarity. Selected bond lengths [Å]: C1–C2 1.421(5), C1–C5 1.407(5), C2–C3 1.440(5), C3–C4 1.399(5), C4–C5 1.459(5), C1–Li1 2.352(8), C2–Li1 2.488(8), C3–Li1 2.586(9), C4–Li1 2.588(9), C5–Li1 2.455(8). C1–O2 1.458(4), Li1–O1 2.250(8).

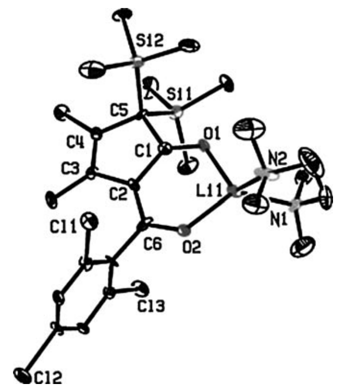
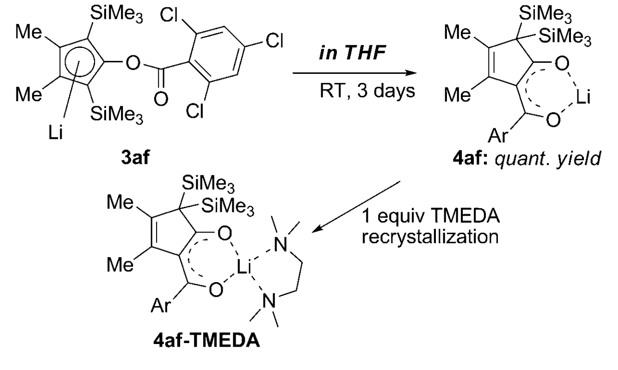


Figure 3. ORTEP drawing of **4af-TMEDA** with 10 % thermal ellipsoids. Hydrogen atoms are omitted for clarity. Selected bond lengths [Å]: C1–C2 1.500(7), C1–C5 1.561(8), C2–C3 1.502(7), C2–C6 1.440(7), C3–C4 1.384(7), C4–C5 1.556(7), C1–O1 1.258(7), C6–O2 1.297(7), O1–Li1 1.922(11), O2–Li1 1.946(10).

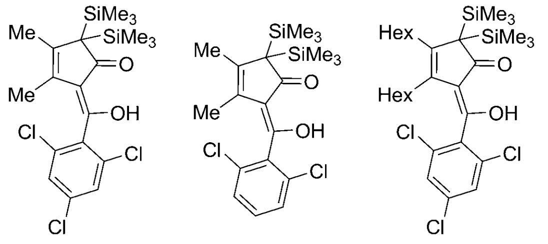
of **3**. The protonated intermediate **8** is proposed to undergo a fast[1,3] sigmatropic silyl shift due to the suitable configuration for σ-π hyperconjugation.[12] This hypothesis was further supported by the formation of **9**. The X-ray structure of **9** revealed that the second acyl group is attached to the C3 of the cyclopentadienyl ring (see the Supporting Information). No silyl shift took place when the C3 was captured.

As mentioned above, the aggregation pattern of organolithium compounds remarkably influences the formation of products **5**. We then dissolved compound **3af** in tetrahydrofuran (THF) because THF is known to be able to de-aggregate organolithium compounds and trigger the Brook rearrangement.[7g] The THF solution was kept at room temperature and monitored by NMR spectroscopy (Scheme 3). Interestingly, the in situ recorded NMR spectra clearly demonstrated that compound **3af** slowly transformed into the different compound **4af** within three days (see the Supporting Information for detailed NMR spectra). Recrystallization of **4af** with 1 equivalent of TMEDA from diethyl ether afforded the suitable single crystals **4af-TMEDA**. The structure of **4af-TMEDA** was determined by single-crystal X-ray structural analysis (Figure 3). It features a monomeric chelate enolate lithium structure.[13] Two nitrogen atoms of TMEDA and two oxygen atoms form the tetrahedral coordination geometry around Li1. The coordination of one delocalized -OC_3O- unit with one negative charge (analogous to the acetylacetonate ligand) to the Li center leads to the formation of the six-membered ring. Hydrolysis of the isolated intermediate **4af** led to its corresponding product **5af** in a quantitative yield.



Scheme 3. Observation of the novel transformation in THF and isolation of the chelate enolate lithium intermediates. Ar = 2,4,6-trichlorophenyl.

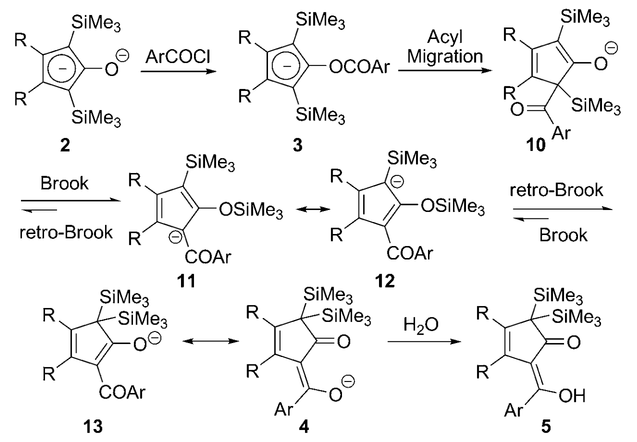
Inspired by the above mentioned THF-promoted transformation, we applied this experimental protocol to more substrates, which are shown in Table 2. Products **5af**, **5ag**, and **5cf** were obtained as sole products in good yields (Figure 4).



5af (from **1a**): 65% **5ag** (from **1a**): 68% **5cf** (from **1c**): 60%

Figure 4. Formation of *gem*-bis(trimethylsilyl) cyclopentenones containing a stable enol moiety from bulky ArCOCl in THF.

A proposed mechanism for the formation of **5** is given in Scheme 4. First, the oxyanion of **2** was trapped by acid chloride and formed the Cp anion species **3**. Next, sequential acyl migration of **3** led to **10**. After Brook rearrangement, the anion was relayed back to the Cp with the help of silyl migration for the first time generating **11**, as the resonance form of **12**, which was stabilized by α-effect of silyl group.[14] Finally, the retro-Brook rearrangement occurred along with



Scheme 4. Proposed mechanism for the formation of *gem*-bis(trimethylsilyl) cyclopentenones containing a stable enol moiety.

silyl migration for the second time and the oxyanion was regenerated forming **13** or **4**.

In summary, we have developed a novel dianionic relay linchpin. Key intermediates were obtained to confirm the proposed process, in which the anion was relayed iteratively along the Cp ring with the exocyclic oxyanion as the post-house.

Acknowledgements

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Keywords: anion relay chemistry · cyclopentadienyl ligands · dilithio reagents · silyl groups · reactive intermediates

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