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[60]Fullerene-Fused Lactones: Manganese(III) Acetate-Mediated Synthesis and Novel Reductive Ring Opening

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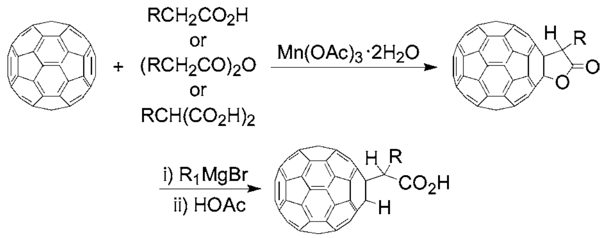
ABSTRACT



[60]Fullerene-fused lactones were prepared by the manganese(III) acetate-mediated reactions of [60]fullerene with carboxylic acids, carboxylic anhydrides, or malonic acids. Novel reductive ring opening of the lactones with Grignard reagents was observed.

Free-radical reactions[1] were one of the first investigated reactions of fullerenes and continue to be of interest as important methodologies to functionalize fullerenes.[2] Over the past decades, manganese(III)-mediated free-radical reactions have been explored extensively, have found widespread applications in organic synthesis, and have demonstrated remarkable advantages over traditional peroxide- or light-initiated processes.[3] We were the first to report the free-radical reactions of [60]fullerene (C_{60}) promoted by manganese(III) acetate dihydrate ($Mn(OAc)_3{\cdot}2H_2O$).[4] The $Mn(OAc)_3{\cdot}2H_2O$-mediated reactions of C_{60} with various active methylene compounds and aromatic methyl ketones afforded 1,4-adducts and 1,16-adducts of C_{60},[4a,b] singly bonded fullerene dimers,[4a] dihydrofuran-fused C_{60} derivatives,[4c] and methanofullerenes.[4a,c] In our recent work, we found that the in situ generated $ArC_{60}{-}H$ could be transformed to $ArC_{60}{-}OAc$ by $Mn(OAc)_3{\cdot}2H_2O$ in a one-pot procedure.[4d]

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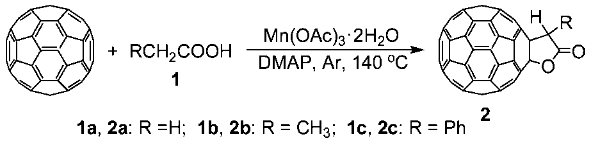
Up to now, only a few examples of fullerenyl esters are known,[4d,5] and only one paper describing the lactonization of two C_{60} adducts was reported.[6] The synthesis of the two fullerenyl lactones required three steps starting from C_{60}. In continuation of our interest in fullerene chemistry,[4,7] in this paper, we report the facile one-step synthesis of C_{60}-fused lactones by the $Mn(OAc)_3 \cdot 2H_2O$-mediated reactions of C_{60} with carboxylic acids, with carboxylic anhydrides, or with malonic acids. Furthermore, these C_{60}-fused lactones were found to undergo novel reductive ring opening with Grignard reagents.

It is well-known that γ-lactones can be synthesized by the reactions of alkenes with acetic acid and substituted acetic acids in the presence of $Mn(OAc)_3$.[8] Carboxylate ions that act as the bases for the deprotonation of the carboxylic acids were found to accelerate the lactonizations.[8b−d] We therefore investigated the reactions of C_{60} with acetic acid (**1a**), propionic acid (**1b**), and phenylacetic acid (**1c**) in the presence of $Mn(OAc)_3 \cdot 2H_2O$ and 4-(dimethylamino)pyridine (DMAP) to obtain the C_{60}-fused lactones. Much to our satisfaction, the $Mn(OAc)_3 \cdot 2H_2O$-mediated reactions of C_{60} with **1a**−**c** afforded C_{60}-annulated lactones **2a**−**c** (Scheme 1).

Scheme 1



The reaction conditions and yields of **2a**−**c** are listed in Table 1. As seen from Table 1, both acetic acid and substituted acetic acids (i.e., methyl-substituted (**1b**) and phenyl-substituted (**1c**)) gave the desired lactones in very high yields (>90%) based on consumed C_{60}. Phenylacetic acid was more reactive and afforded higher isolated yields presumably because the phenyl group could stabilize the formed α-*C*H radical (vide infra). Lactones **2a**−**c** were fully characterized by MS, ^1H NMR, ^{13}C NMR, IR, and UV−vis spectra. The typical chemical shifts at 171−177 ppm in the ^{13}C NMR spectra and the absorptions at 1784−1789 cm^{-1} in the IR spectra of **2a**−**c** indicated the presence of the lactone moiety. The structure of **2b** was confirmed by comparison of its spectral data with those reported previously.[6]

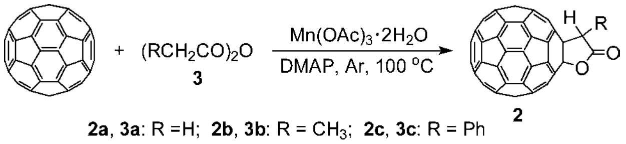
Table 1. Reaction Times and Yields for the $Mn(OAc)_3 \cdot 2H_2O$-Mediated Reaction of C_{60} with Acids **1a**−**c** in the Presence of DMAP[a]

product	R	reaction time (h)	yield (%)[b]
2a	H	1	24 (92)
2b	CH_3	1	27 (93)
2c	Ph	0.5	34 (92)

[a] All reactions were performed in *o*-dichlorobenzene (ODCB) at 140 °C under an argon atmosphere. Molar ratio of C_{60}:**1a** or **1b**:$Mn(OAc)_3 \cdot 2H_2O$:DMAP = 1:100:2:1; molar ratio of C_{60}:**1c**:$Mn(OAc)_3 \cdot 2H_2O$:DMAP = 1:20:2:1. [b] Isolated yield. That in parentheses was based on consumed C_{60}.

Acetic anhydride was added to increase both the rate and the yield of the reaction of alkenes with acetic acid.[8a] However, it was later reported that the addition of acetic anhydride had deleterious effects on the lactonization.[8d] Carboxylic anhydrides have not been used alone for the lactonization of alkenes. We found that lactones **2a**−**c** could be successfully prepared by the reactions of C_{60} with corresponding carboxylic anhydrides **3**, $Mn(OAc)_3 \cdot 2H_2O$, and DMAP (Scheme 2).

Scheme 2



The reaction conditions and yields of **2a**−**c** for the $Mn(OAc)_3 \cdot 2H_2O$-mediated reactions of C_{60} with acetic anhydride (**3a**), propionic anhydride (**3b**), or phenylacetic anhydride (**3c**) in the presence of DMAP are listed in Table 2. As seen from Table 2, excellent yields (~90%) based on converted C_{60} were also achieved with carboxylic anhydrides as the reagents.

Table 2. Yields of **2a**−**c** for the $Mn(OAc)_3 \cdot 2H_2O$-Mediated Reaction of C_{60} with Anhydrides **3a**−**c** in the Presence of DMAP[a]

product	R	yield (%)[b]
2a	H	37 (87)
2b	CH_3	36 (93)
2c	Ph	26 (92)

[a] All reactions were performed in ODCB at 100 °C for 1 h under an argon atmosphere. Molar ratio of C_{60}:**3a**/**3b**/**3c**:$Mn(OAc)_3 \cdot 2H_2O$:DMAP = 1:20:2:1. [b] Isolated yield. That in parentheses was based on consumed C_{60}.

It should be noted that DMAP played a crucial role in the successful synthesis of lactones **2a**−**c** from both carboxylic acids and anhydrides. No lactones **2a**−**c** were obtained with carboxylic anhydrides **3a**−**c** as the reagents in the absence

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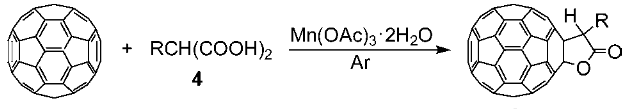
of DMAP. As for carboxylic acids **1a**−**c**, byproducts were formed without the addition of DMAP. Other bases such as pyridine, triethylamine, and triethylenediamine were examined and found to be inferior to DMAP.

Malonic acid (**4a**) was reported to react with alkenes to give spirodilactones in the presence of $Mn(OAc)_3{\cdot}2H_2O$.[9] We explored the $Mn(OAc)_3{\cdot}2H_2O$-mediated reaction of C_{60} with **4a** to see if we could obtain a spirodilactone-bridged fullerene dimer. However, we obtained lactone **2a** rather than a spirodilactone-bridged fullerene dimer in the presence or absence of DMAP. Therefore, methylmalonic acid (**4b**) and phenylmalonic acid (**4c**) along with **4a** were employed in the $Mn(OAc)_3{\cdot}2H_2O$-mediated reactions of C_{60} to develop the third route to C_{60}-annulated lactones (Scheme 3).

Scheme 3



2a, **4a**: R = H; **2b**, **4b**: R = CH_3; **2c**, **4c**: R = Ph

The $Mn(OAc)_3{\cdot}2H_2O$-mediated reactions of C_{60} with **4a**−**c** proceeded faster and could occur at lower temperatures. The reaction conditions and product yields for the reactions with **4a**−**c** at 25 and 80 °C are collected in Table 3. The data in Table 3 show that substituted malonic acids can react with C_{60} at room temperature in the presence of $Mn(OAc)_3{\cdot}2H_2O$, whereas malonic acid itself requires a higher temperature to react. This fact is consistent with the easier formation and higher stability of the in situ generated radicals from the former.

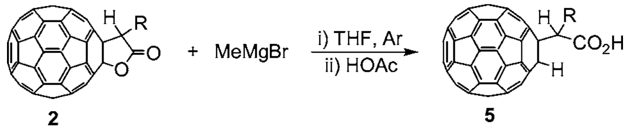
Table 3. Product Yields for the $Mn(OAc)_3{\cdot}2H_2O$-Mediated Reaction of C_{60} with Malonic Acids **4a**−**c**[a]

product	R	reaction temp (°C)	reaction time (min)	yield (%)[b]
2a	H	80	60	34 (85)
		25	180	trace
2b	CH_3	80	5	41 (85)
		25	60	35 (90)
2c	Ph	80	60	24 (80)
		25	120	18 (75)

[a] All reactions were performed in ODCB/DMF under an argon atmosphere. Molar ratio of C_{60}:**4a**/**4b**/**4c**:$Mn(OAc)_3{\cdot}2H_2O$ = 1:20:2. [b] Isolated yield. That in parentheses was based on consumed C_{60}.

The lactone group of products **2a**−**c** can undergo many further functionalizations. In an attempt to open the lactone rings of **2a**−**c** by reaction with CH_3MgBr in THF, we unexpectedly discovered the novel reductive opening of the lactone rings after quenching with HOAc (Scheme 4).

Scheme 4



2a, **5a**: R = H; **2b**, **5b**: R = CH_3; **2c**, **5c**: R = Ph

The reaction conditions, yields of **5a**−**c** along with recovered **2a**−**c**, for the reductive ring opening of lactones **2a**−**c** with CH_3MgBr in THF are listed in Table 4.

Table 4. Yields and Recovered **2a**−**c** for the Reactions of **2a**−**c** with CH_3MgBr[a]

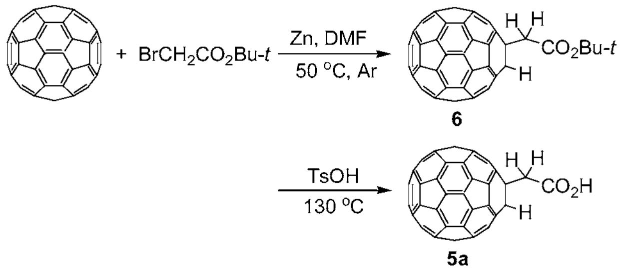
product	R	yield (%)[b]	recovered **2** (%)
5a	H	52	40
5b	CH_3	93	trace
5c	Ph	45	52

[a] All reactions were performed in THF at 20 °C for 10 min under an argon atmosphere and then quenched with HOAc. Molar ratio of **2**:CH_3MgBr = 1:12. [b] Isolated yield.

The structures of products **5a**−**c** were fully established by their MS, ^{1}H NMR, ^{13}C NMR, IR, and UV−vis spectra. All products **5a**−**c** exhibited correct molecular weights in their mass spectra. Comparing the spectra of **5a**−**c** with those of **2a**−**c**, we found that new singlets in the ^{1}H NMR spectra of **5a**−**c** appeared at 6.9−7.0 ppm, the typical chemical shift for a proton attached to the C_{60} core. The peaks at 96−97 ppm in the ^{13}C NMR spectra of **2a**−**c** were shifted upfield to 58−59 ppm in those of **5a**−**c**, consistent with the change of the sp^3-C of C_{60} from C_{60}−O in **2a**−**c** to C_{60}−H in **5a**−**c**; the absorptions at 1784−1789 cm^{-1} in the IR spectra of **2a**−**c** moved to 1703−1729 cm^{-1} in those of **5a**−**c**, corresponding to the change of the lactone moiety in **2a**−**c** to the carboxylic acid group in **5a**−**c**.

The identity of compound **5a** was further confirmed by the fact that it was the same as that prepared from the reactions shown in Scheme 5. Compound **6** was prepared in 11% yield by the reaction of C_{60} with *tert*-butyl bromoacetate and zinc according to the reported procedure.[10] Heating

Scheme 5



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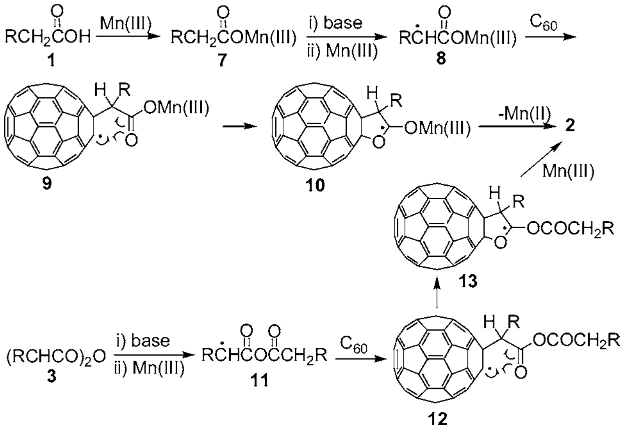
compound **6** in chlorobenzene at 130 °C in the presence of *p*-toluenesulfonic acid afforded product **5a** in 99% yield.

On the basis of the previously suggested mechanism for the lactone formation from alkenes and acetic acid,[8d] the proposed mechanism for the formation of C_{60}-fused lactones **2a**−**c** from C_{60} and carboxylic acids **1a**−**c** and carboxylic anhydrides **3a**−**c** is shown in Scheme 6.

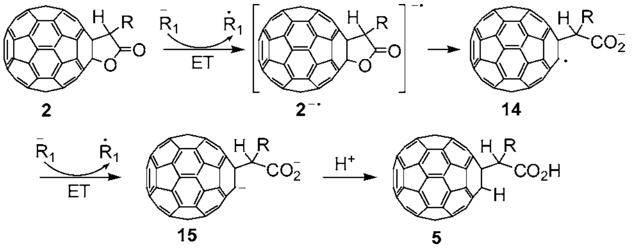
Scheme 6



Carboxylic acids **1a**−**c** react with $Mn(OAc)_3{\cdot}2H_2O$ to give manganese(III) carboxylates **7a**−**c**, which are deprotonated at the α-carbon by DMAP, followed by oxidation with another molecule of $Mn(OAc)_3{\cdot}2H_2O$ to generate radicals **8a**−**c**. Addition of radicals **8a**−**c** to C_{60} produces fullerenyl radicals **9a**−**c**, which cyclize to radicals **10a**−**c**. Loss of Mn(II) species from **10a**−**c** affords **2a**−**c**. Carboxylic anhydrides **3a**−**c** can be deprotonated by DMAP, followed by oxidation with $Mn(OAc)_3{\cdot}2H_2O$, to give radicals **11a**−**c**, which add to C_{60} to generate fullerenyl radicals **12a**−**c**. Cyclization of radicals **12a**−**c** to **13a**−**c** and subsequent oxidation by a second molecule of $Mn(OAc)_3{\cdot}2H_2O$ produce **2a**−**c**. As for malonic acids **4a**−**c**, the reactions probably proceed via radicals **8a**−**c**, which are generated from **4a**−**c** under the action of $Mn(OAc)_3{\cdot}2H_2O$; the subsequent reactions with C_{60} are the same as those shown in Scheme 6.

It is noteworthy that CH_3MgBr behaved abnormally toward lactones **2a**−**c** and did not add to the carbonyl group of lactones **2a**−**c** in THF to give the corresponding hemiketals or tertiary alcohols. The reduction of ketones by Grignard reagents involving the *β*-H transfer via a cyclic six-membered transition state has been reported.[11] However, the reduction of lactones by Grignard reagents, especially by CH_3MgBr that lacks *β*-H, is not known. Because PhMgBr also reacted with **2a**−**c** to give **5a**−**c** and the reaction mixture with these Grignard reagents turned dark green, the typical color of a fullerenyl anion,[12] a possible mechanism for the formation of **5a**−**c** is shown in Scheme 7. Fullerenes and their derivatives are known to be good electron acceptors. Electron transfer from the Grignard reagent to **2a**−**c** gives the radical anions of **2a**−**c**, which transform into intermediates **14a**−**c** via the rapture of the C−O bond. Further electron transfer from the Grignard reagent to **14a**−**c** generates dianions **15a**−**c**, and subsequent protonation with HOAc affords **5a**−**c**.

Scheme 7



In summary, C_{60}-fused lactones can be synthesized by the $Mn(OAc)_3{\cdot}2H_2O$-mediated reactions of C_{60} with carboxylic acids, carboxylic anhydrides, or malonic acids. The novel reductive ring opening of the obtained lactones by Grignard reagents has been observed.

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Supporting Information Available: Detailed experimental procedures and characterization data, as well as the ^1H NMR and ^{13}C NMR spectra of **2a** and **5a**. This material is available free of charge via the Internet at http://pubs.acs.org.

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