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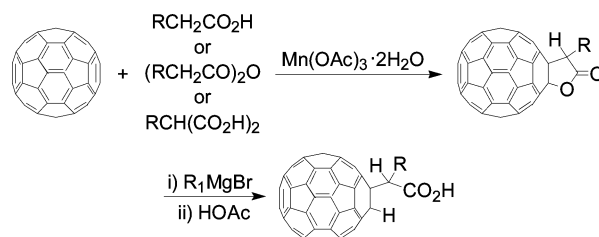
Guan-Wu Wang,* Fa-Bao Li, and Ting-Hu Zhang

Hefei National Laboratory for Physical Sciences at Microscale and Department of Chemistry, University of Science and Technology of China, Hefei, Anhui 230026, PRC

gwang@ustc.edu.cn

Received January 12, 2006

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 reactions¹ 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 ($\text{Mn}(\text{OAc})_3 \cdot 2\text{H}_2\text{O}$).⁴ The $\text{Mn}(\text{OAc})_3 \cdot 2\text{H}_2\text{O}$ -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 $\text{ArC}_{60}\text{--H}$ could be transformed to $\text{ArC}_{60}\text{--OAc}$ by $\text{Mn}(\text{OAc})_3 \cdot 2\text{H}_2\text{O}$ in a one-pot procedure.^{4d}

(1) (a) Krusic, P. J.; Wasserman, E.; Keizer, P. N.; Morton, J. R.; Preston, K. F. *Science* **1991**, 254, 1183. (b) Krusic, P. J.; Wasserman, E.; Parkinson, B. A.; Malone, B.; Holler, E. R., Jr.; Keizer, P. N.; Morton, J. R.; Preston, K. F. *J. Am. Chem. Soc.* **1991**, 113, 6274.

(2) For recent examples, see: (a) Gan, L.; Huang, S.; Zhang, X.; Zhang, A.; Cheng, B.; Cheng, H.; Li, X.; Shang, G. *J. Am. Chem. Soc.* **2002**, 124, 13384. (b) Darwish, A. D.; Avent, A. G.; Abdul-Sada, A. K.; Taylor, R. *Chem. Commun.* **2003**, 1374. (c) Maeda, Y.; Rahman, G. M. A.; Wakahara, T.; Kako, M.; Okamura, M.; Sato, S.; Akasaka, T.; Kobayashi, K.; Nagase, S. *J. Org. Chem.* **2003**, 68, 6791. (d) Huang, S.; Xiao, Z.; Wang, F.; Gan, L.; Zhang, X.; Hu, X.; Zhang, S.; Lu, M.; Pan, Q.; Xu, L. *J. Org. Chem.* **2004**, 69, 2442. (e) Li, C.; Zhang, D.; Zhang, X.; Wu, S.; Gao, X. *Org. Biomol. Chem.* **2004**, 2, 3464. (f) Vougioukalakis, G. C.; Orfanopoulos, M. *J. Am. Chem. Soc.* **2004**, 126, 15956. (g) Xiao, Z.; Wang, F.; Huang, S.; Gan, L.; Zhou, J.; Yuan, G.; Lu, M.; Pan, J. *J. Org. Chem.* **2005**, 70, 2060. (h) Isobe, H.; Tanaka, T.; Nakanishi, W.; Lemiègre, L.; Nakamura, E. *J. Org. Chem.* **2005**, 70, 4826. (i) Kareev, I. E.; Kuvychko, I. V.; Lebedkin, S. F.; Miller, S. M.; Anderson, O. P.; Seppelt, K.; Strauss, S. H.; Boltalina, O. V. *J. Am. Chem. Soc.* **2005**, 127, 8362. (j) Nakamura, Y.; Suzuki, M.; O-kawa, K.; Konno, T.; Nishimura, J. *J. Org. Chem.* **2005**, 70, 8472.

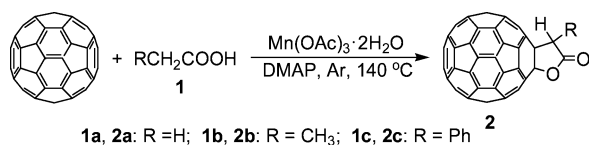
(3) For reviews, see: (a) Melikyan, G. G. *Synthesis* **1993**, 833. (b) Iqbal, J.; Bhatia, B.; Nayyar, N. K. *Chem. Rev.* **1994**, 94, 519. (c) Snider, B. B. *Chem. Rev.* **1996**, 96, 339. For recent examples of manganese(III)-based radical reactions, see: (d) Zhang, Z.; Wang, G.-W.; Miao, C.-B.; Dong, Y.-W.; Shen, Y.-B. *Chem. Commun.* **2004**, 1832. (e) Zhou, H.; Huang, X.; Chen, W. *J. Org. Chem.* **2004**, 69, 5471. (f) Huang, J.-W.; Shi, M. *J. Org. Chem.* **2005**, 70, 3859.

(4) (a) Zhang, T.-H.; Lu, P.; Wang, F.; Wang, G.-W. *Org. Biomol. Chem.* **2003**, 1, 4403. (b) Wang, G.-W.; Zhang, T.-H.; Cheng, X.; Wang, F. *Org. Biomol. Chem.* **2004**, 2, 1160. (c) Wang, G.-W.; Li, F.-B. *Org. Biomol. Chem.* **2005**, 3, 794. (d) Chen, Z.-X.; Wang, G.-W. *J. Org. Chem.* **2005**, 70, 2380.

Up to now, only a few examples of fullereryl esters are known,^{4d,5} and only one paper describing the lactonization of two C₆₀ adducts was reported.⁶ The synthesis of the two fullereryl lactones required three steps starting from C₆₀. In continuation of our interest in fullerene chemistry,^{4,7} in this paper, we report the facile one-step synthesis of C₆₀-fused lactones by the Mn(OAc)₃·2H₂O-mediated reactions of C₆₀ with carboxylic acids, with carboxylic anhydrides, or with malonic acids. Furthermore, these C₆₀-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 C₆₀ with acetic acid (**1a**), propionic acid (**1b**), and phenylacetic acid (**1c**) in the presence of Mn(OAc)₃·2H₂O and 4-(dimethylamino)pyridine (DMAP) to obtain the C₆₀-fused lactones. Much to our satisfaction, the Mn(OAc)₃·2H₂O-mediated reactions of C₆₀ with **1a–c** afforded C₆₀-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 C₆₀. Phenylacetic acid was more reactive and afforded higher isolated yields presumably because the phenyl group could stabilize the formed α -CH radical (vide infra). Lactones **2a–c** were fully characterized by MS, ¹H NMR, ¹³C NMR, IR, and UV–vis spectra. The typical chemical shifts at 171–177 ppm in the ¹³C 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

(5) (a) Irngartinger, H.; Weber, A. *Tetrahedron Lett.* **1997**, 38, 2075. (b) Irngartinger, H.; Weber, A.; Escher, T. *Eur. J. Org. Chem.* **2000**, 1647. (c) Zhdankin, V. V.; Hanson, K. J.; Kuposov, A. E.; Blomquist, E.; Tykwinski, R. R. *Mendeleev Commun.* **2001**, 11, 51.

(6) Bernstein, R.; Foote, C. S. *Tetrahedron Lett.* **1998**, 39, 7051.

(7) For examples, see: (a) Wang, G.-W.; Zhang, X.-H.; Zhan, H.; Guo, Q.-X.; Wu, Y.-D. *J. Org. Chem.* **2003**, 68, 6732. (b) Wang, G.-W.; Li, J.-X.; Li, Y.-J.; Liu, Y.-C. *J. Org. Chem.* **2006**, 71, 680.

(8) (a) Bush, J. B., Jr.; Finkbeiner, H. *J. Am. Chem. Soc.* **1968**, 90, 5903. (b) Heiba, E. I.; Dessau, R. M.; Koehl, W. J., Jr. *J. Am. Chem. Soc.* **1968**, 90, 5905. (c) Heiba, E. I.; Dessau, R. M.; Rodewald, P. G. *J. Am. Chem. Soc.* **1974**, 96, 7977. (d) Fristad, W. E.; Peterson, J. R. *J. Org. Chem.* **1985**, 50, 10.

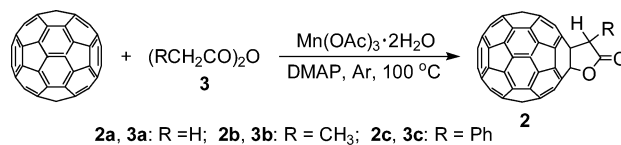
Table 1. Reaction Times and Yields for the Mn(OAc)₃·2H₂O-Mediated Reaction of C₆₀ with Acids **1a–c** in the Presence of DMAP^a

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 C₆₀:**1a** or **1b**:Mn(OAc)₃·2H₂O:DMAP = 1:100:2:1; molar ratio of C₆₀:**1c**:Mn(OAc)₃·2H₂O:DMAP = 1:20:2:1. ^b Isolated yield. That in parentheses was based on consumed C₆₀.

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 C₆₀ with corresponding carboxylic anhydrides **3**, Mn(OAc)₃·2H₂O, and DMAP (Scheme 2).

Scheme 2



The reaction conditions and yields of **2a–c** for the Mn(OAc)₃·2H₂O-mediated reactions of C₆₀ with acetic anhydride (**3a**), propionic anhydride (**3b**), or phenylacetic anhydride (**3c**) in the presence of DMAP are listed in Table 2. As seen

Table 2. Yields of **2a–c** for the Mn(OAc)₃·2H₂O-Mediated Reaction of C₆₀ 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 C₆₀:**3a/3b/3c**:Mn(OAc)₃·2H₂O:DMAP = 1:20:2:1. ^b Isolated yield. That in parentheses was based on consumed C₆₀.

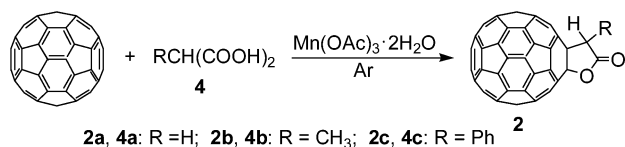
from Table 2, excellent yields (~90%) based on converted C₆₀ were also achieved with carboxylic anhydrides as the reagents.

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

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 $\text{Mn}(\text{OAc})_3 \cdot 2\text{H}_2\text{O}$.⁹ We explored the $\text{Mn}(\text{OAc})_3 \cdot 2\text{H}_2\text{O}$ -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 $\text{Mn}(\text{OAc})_3 \cdot 2\text{H}_2\text{O}$ -mediated reactions of C_{60} to develop the third route to C_{60} -annulated lactones (Scheme 3).

Scheme 3



The $\text{Mn}(\text{OAc})_3 \cdot 2\text{H}_2\text{O}$ -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. Product Yields for the $\text{Mn}(\text{OAc})_3 \cdot 2\text{H}_2\text{O}$ -Mediated Reaction of C_{60} with Malonic Acids **4a–c**^a

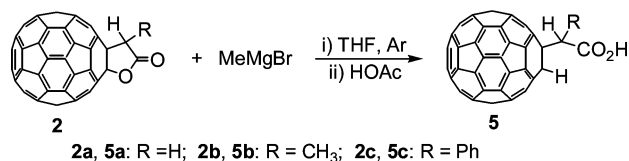
product	R	reaction temp (°C)	reaction time (min)	yield (%) ^b
2a	H	80	60	34 (85)
		25	180	trace
2b	CH ₃	80	5	41 (85)
		25	60	35 (90)
2c	Ph	80	60	24 (80)
		25	120	18 (75)

^a All reactions were performed in ODCB/DMF under an argon atmosphere. Molar ratio of C_{60} :**4a/4b/4c**: $\text{Mn}(\text{OAc})_3 \cdot 2\text{H}_2\text{O}$ = 1:20:2. ^b Isolated yield. That in parentheses was based on consumed C_{60} .

Table 3 show that substituted malonic acids can react with C_{60} at room temperature in the presence of $\text{Mn}(\text{OAc})_3 \cdot 2\text{H}_2\text{O}$, 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.

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



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

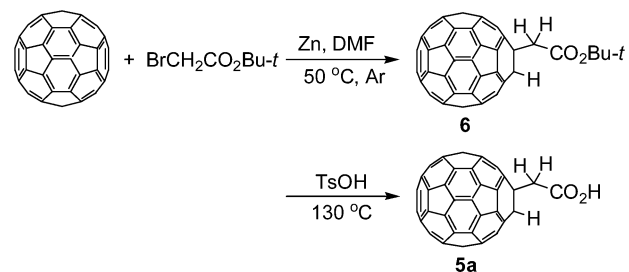
product	R	yield (%) ^b	recovered 2 (%)
5a	H	52	40
5b	CH ₃	93	trace
5c	Ph	45	52

^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, ¹H NMR, ¹³C 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 ¹H 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 ¹³C NMR spectra of **2a–c** were shifted upfield to 58–59 ppm in those of **5a–c**, consistent with the change of the $\text{sp}^3\text{-C}$ of C_{60} from $\text{C}_{60}\text{-O}$ in **2a–c** to $\text{C}_{60}\text{-H}$ 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

Scheme 5



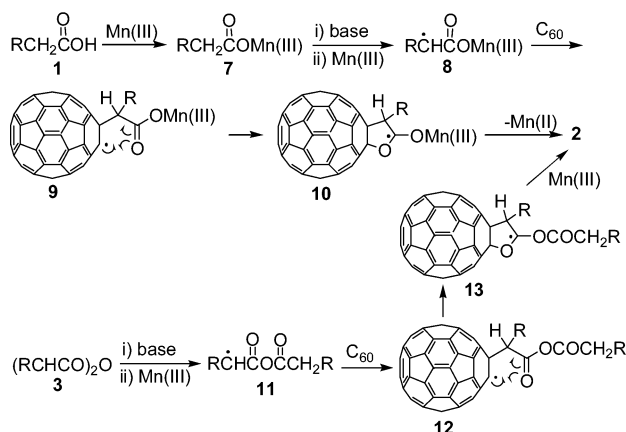
11% yield by the reaction of C_{60} with *tert*-butyl bromoacetate and zinc according to the reported procedure.¹⁰ Heating

(9) (a) Ito, N.; Nishino, H.; Kurosawa, K. *Bull. Chem. Soc. Jpn.* **1983**, 56, 3527. (b) Fristad, W. E.; Hershberger, S. S. *J. Org. Chem.* **1985**, 50, 1026.

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 C₆₀-fused lactones **2a–c** from C₆₀ and carboxylic acids **1a–c** and carboxylic anhydrides **3a–c** is shown in Scheme 6.

Scheme 6

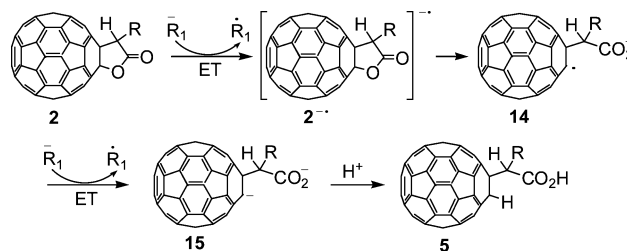


Carboxylic acids **1a–c** react with Mn(OAc)₃·2H₂O to give manganese(III) carboxylates **7a–c**, which are deprotonated at the α-carbon by DMAP, followed by oxidation with another molecule of Mn(OAc)₃·2H₂O to generate radicals **8a–c**. Addition of radicals **8a–c** to C₆₀ produces fullerene radicals **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)₃·2H₂O, to give radicals **11a–c**, which add to C₆₀ to generate fullerene radicals **12a–c**. Cyclization of radicals **12a–c** to **13a–c** and subsequent oxidation by a second molecule of Mn(OAc)₃·2H₂O 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)₃·2H₂O; the subsequent reactions with C₆₀ are the same as those shown in Scheme 6.

It is noteworthy that CH₃MgBr behaved abnormally toward lactones **2a–c** and did not add to the carbonyl group of lactones **2a–c** in THF to give the corresponding hemiket-

als 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 CH₃MgBr 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 fullerene anion,¹² a possible mechanism for the formation of **5a–c** is shown in Scheme 7. Fullerenes and their

Scheme 7



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 rupture 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**.

In summary, C₆₀-fused lactones can be synthesized by the Mn(OAc)₃·2H₂O-mediated reactions of C₆₀ with carboxylic acids, carboxylic anhydrides, or malonic acids. The novel reductive ring opening of the obtained lactones by Grignard reagents has been observed.

Acknowledgment. The authors are grateful for the financial support from the National Natural Science Foundation of China (Nos. 20572105, 20321101, and 20125205) and Anhui Provincial Bureau of Personnel Affairs (2001Z019).

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

OL060090Y

(11) (a) Morrison, J. D.; Tomaszewski, J. E.; Mosher, H. S.; Dale, J.; Miller, D.; Elsenbaumer, R. L. *J. Am. Chem. Soc.* **1977**, *99*, 3167. (b) Sassian, M.; Tuulmets, A. *Helv. Chim. Acta* **2003**, *86*, 82.

(12) Murata, Y.; Komatsu, K.; Wan, T. S. M. *Tetrahedron Lett.* **1996**, *37*, 7061.

(10) Wang, Z.; Meier, M. S. *J. Org. Chem.* **2003**, *68*, 3043.