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# A new synthesis of fullerenyl ketones catalyzed by Ti(O*i*-Pr)$_4$

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ABSTRACT

The reaction of fullerene $C_{60}$ with aryl carboxylates and EtMgBr in the presence of Ti(O*i*-Pr)$_4$ as the catalyst leads to the formation of novel fullerenyl ketones.

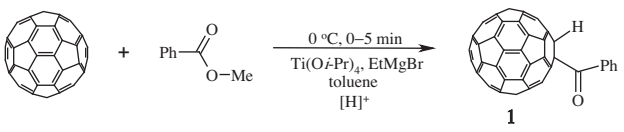


Functionalized fullerenes are very attractive systems from a practical point of view, with most examples being fulleropyridines and methanofullerenes.

While the synthesis of fulleropyridines is mainly carried out under the Prato reaction conditions,[1] methods for synthesizing methanofullerenes are based predominantly upon two processes: the reaction between fullerenes and in situ generated α-halogeno-carbanions (the Bingel–Hirsch reaction),[2–4] or the cycloaddition of diazo compounds to these carbon clusters.[5]

The Bingel–Hirsch reaction is widely used as a preparative method for the synthesis of methanofullerenes as promising substances of high value.[6,7] On the other hand, the reactions of fullerenes with diazo compounds have wide synthetic potential leading to not only methanofullerenes, but also homo- and pyrazolinofullerenes.[8–16]

In our search for a new and effective method to functionalize fullerenes, we focused on the known Kulinkovich reaction,[17–20] which allows the synthesis of cyclopropanols in high yields from olefins, carboxylates, and EtMgBr in the presence of Ti complexes.

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**Scheme 1.** Synthesis of fullerenyl ketone **1** via the Ti(O*i*-Pr)$_4$-catalyzed reaction of fullerene $C_{60}$ with methyl benzoate and ethylmagnesium bromide in toluene.

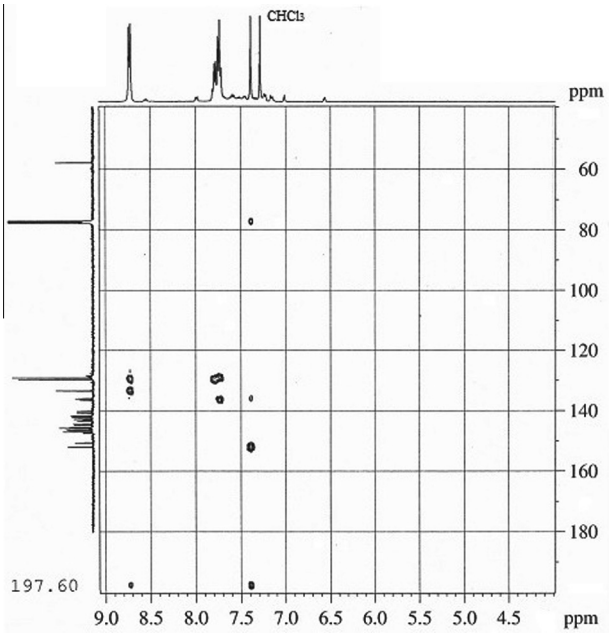


**Figure 1.** The HMBC spectrum of compound **1** (400.13 MHz for $^1$H, 100.62 MHz for $^{13}$C, solvent = $CS_2$–$CDCl_3$, 5:1).

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We hypothesized that the use of fullerene in this reaction, instead of an olefin, would simplify the preparation of methanofullerenes with different functional groups at the bridge carbon atom, the synthesis of which usually requires multi-step procedures.

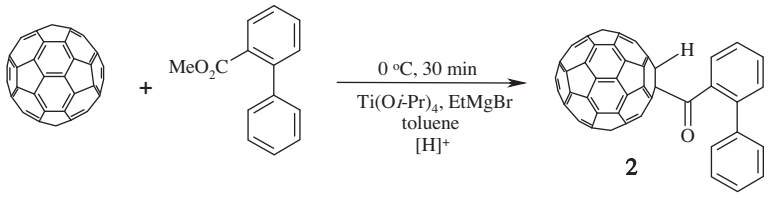
However, the reaction between fullerene $C_{60}$ and aryl carboxylates under the Kulinkovich reaction conditions did not lead to the target [2+1] cycloadducts. In each case, instead of the desired methanofullerene, we obtained the previously undescribed fullerenyl ketones.

These unexpected results prompted us to study this reaction in detail focusing on the reaction between fullerene $C_{60}$ and methyl benzoate in the presence of EtMgBr and a Ti-containing complex catalyst. Our preliminary experiments revealed that the best results were achieved while using Ti(O*i*-Pr)$_4$ as the catalyst and EtMgBr under mild reaction conditions (0 °C, 5–10 min, toluene).

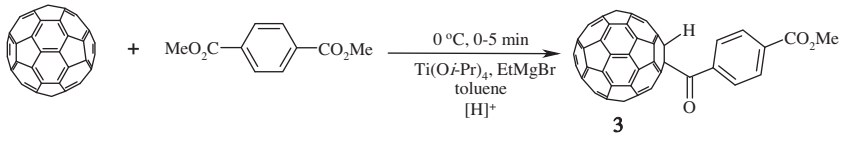
Thus, fullerene $C_{60}$, under an argon atmosphere, underwent a reaction with methyl benzoate and EtMgBr in the presence of Ti(O*i*-Pr)$_4$ (1:10:40:10 molar ratio) in toluene at 0 °C[21] to give predominantly phenyl fullerenyl ketone **1**[22] in 57% yield after hydrolysis of the reaction mixture with 5% aqueous HCl (Scheme 1). An increase in temperature (20 °C) contributed to the formation, along with the target adduct **1**, of by-products, namely, 1,2-dihydrofullerene and 1-ethyl-1,2-dihydrofullerene in a 3:3:1 ratio and a total yield of 63%.

Adduct **1** was separated from the reaction mixture by preparative HPLC. The structure of fullerenyl ketone **1** was confirmed by one-dimensional ($^1$H, $^{13}$C) and two-dimensional (HHCOSY, HSQC, and HMBC) NMR experiments.

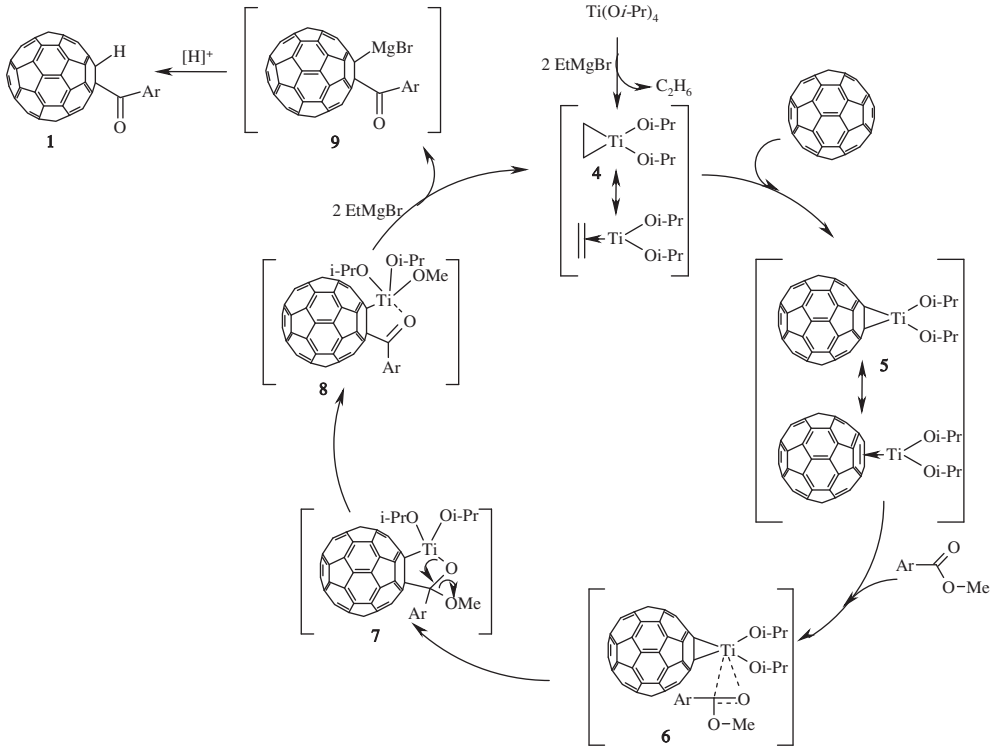
The $^1$H NMR spectrum of **1** contained high frequency resonance signals ($\delta_H$ 7.73, 7.79, and 8.72) characteristic of protons of a phenyl group, as well as a singlet ($\delta_H$ 7.39) due to the hydrogen atom




**Scheme 2.** The synthesis of fullerenyl ketone **2** via catalytic addition of the methyl ester of 1,1′-biphenyl-2-carboxylic acid to fullerene $C_{60}$.




**Scheme 3.** Ti(O*i*-Pr)$_4$-catalyzed reaction of fullerene $C_{60}$ with dimethyl terephthalate and EtMgBr.




**Scheme 4.** A plausible mechanism for the formation of fullerenyl ketone **1**.

attached directly to the fullerene core ($\delta_C$ 57.15). This proton signal ($\delta_H$ 7.39) in the HMBC experiment had cross-peaks with the carbon atoms of the fullerene sphere ($\delta_C$ 152.06 and 77.35), the quaternary carbon atom of the phenyl substituent ($\delta_C$ 136.48), as well as the carbonyl group ($\delta_C$ 197.60) (Fig. 1).

The MALDI TOF mass spectrum of **1** (negative ion mode using elemental sulfur as a matrix) contained an intense molecular ion peak $[M]^-$ at *m/z* 826.037 (ca. 826.041 for $C_{67}H_6O$), which also supported the proposed structure.

Similar results were obtained with the methyl ester of 1,1′-biphenyl-2-carboxylic acid. Under selected reaction conditions (0 °C, 30 min, toluene), this methyl ester entered into the reaction with fullerene $C_{60}$ and EtMgBr in the presence of the Ti(O*i*-Pr)$_4$ catalyst giving rise to biphenyl fullerenyl ketone **2**[23] in 45% yield after hydrolysis of the reaction mixture (Scheme 2).

To further study this reaction, involving two carboxylic groups simultaneously, we reacted fullerene $C_{60}$ and the dimethyl ester of terephthalic acid. Our experiments revealed that only one carboxylic group underwent the reaction to give adduct **3**[24] in 53% isolated yield (Scheme 3). Increasing the duration and temperature of the reaction as well as altering the ratio of the reactants relative to fullerene did not favor the reaction at both ester groups.

Based on our previous results and literature data,[20] we propose a plausible mechanism for the formation of fullerenyl ketones from aryl carboxylates using the model reaction of fullerene $C_{60}$ with methyl benzoate and EtMgBr in the presence of Ti(O*i*-Pr)$_4$ as the catalyst (Scheme 4).

Initially, the reaction between Ti(O*i*-Pr)$_4$ and EtMgBr affords the dialkoxytitanocyclopropane intermediate **4** in equilibrium with the ethylene complex. Displacement of an ethylene molecule from **4** by fullerene $C_{60}$ results in fullero[60]titanacyclopropane **5** as the key intermediate. (Treatment of the latter with 5% aqueous HCl leads to the formation of dihydrofullerene as evidence for the structure **5**).

Subsequent reaction between intermediate **5** and methyl benzoate leads to the formation of fullero[60]oxatitanacyclopentane **7** via the intermediate complex **6**. Intramolecular methoxy group migration across the oxatitanacyclopentane ring of **7** transforms this molecule into β-titanoketone intermediate **8**, which can react with two equivalents of EtMgBr to give organomagnesium compound (OMC) **9** and regenerate **4**, thus completing the catalytic cycle. Finally, hydrolysis of OMC **9** provides fullerenyl ketone **1**.

The absence of the corresponding methanofullerenes among the reaction products is probably due to thermodynamic factors, which hinder the intramolecular transformation of intermediate **8** into fullerocyclopropane. In accord with literature data,[20] these transformations are limiting in the Kulinkovich reaction.

In conclusion, we have developed a convenient and efficient one-pot synthesis of fullerenyl ketones via the reaction between fullerene $C_{60}$, methyl arylcarboxylates, and ethylmagnesium bromide in the presence of Ti(O*i*-Pr)$_4$ as the catalyst.

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21. *General procedure:* A 50 mL glass reactor was charged with $C_{60}$ (20 mg, 0.0278 mmol) in dry toluene (20 mL), the methyl ester benzoic acid (0.03 mL, 0.278 mmol), and Ti(O*i*-Pr)$_4$ (0.08 mL, 0.278 mmol) under an anhydrous argon atmosphere at 0 °C. Next, EtMgBr (1 M solution in $Et_2O$, 1.112 mmol) was added dropwise over 2–3 min. The resulting solution was allowed to warm to rt and stirred for 5–30 min. The mixture was quenched with an 8–10% (aq) solution of HCl. The layers were separated and the organic layer was passed through a column containing a small amount of silica gel (ca. 2 g). The reaction products **1**–**3** and the starting fullerene $C_{60}$ were separated by semi-preparative HPLC using toluene as the eluent.
22. *Phenyl(C$_{60}$-I$_h$)[5,6]fullerene-1(9H)-yl ketone (**1**).* IR: 526, 692, 869, 1009, 1181, 1225, 1428, 1672 cm$^{-1}$. UV ($CHCl_3$), $\lambda_{max}$, nm: 255, 327, 432. $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.39 (s, 1H, $C_{60}$-H), 7.73 (t, 2H, 2CH, $J$ = 7 Hz), 7.79 (t, 1H, CH, $J$ = 7 Hz), 8.72 (d, 2H, 2CH, $J$ = 7 Hz). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$ 57.15, 77.35, 129.10, 129.64, 133.39, 136.00, 136.05, 136.48, 140.19, 140.76, 141.69, 141.73, 141.88, 142.21, 142.27, 142.76, 142.85, 143.16, 143.39, 144.50, 144.78, 145.51, 145.57, 145.59, 145.82, 146.33, 146.34, 146.50, 146.52, 147.03, 147.34, 147.49, 150.68, 152.06, 197.60. MALDI TOF, *m/z* 826.037 $[M]^-$ ($C_{67}H_6O$).
23. *2′-(1′,1″-Biphenyl)(C$_{60}$-I$_h$)[5,6]fullerene-1(9H)-yl ketone (**2**).* IR: 526, 663, 742, 1107, 1260, 1431, 1699 cm$^{-1}$. UV ($CHCl_3$), $\lambda_{max}$, nm: 255, 328, 434. $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.4–7.64 (m, 9H, 9CH), 7.71 (s, 1H, $C_{60}$-H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$ 55.99, 79.36, 127.14, 128.53, 128.99, 129.45, 129.58, 129.88, 130.73, 135.33, 135.99, 138.13, 139.32, 139.56, 140.44, 140.73, 141.21, 141.49, 141.74, 142.04, 142.18, 142.54, 142.71, 143.16, 144.14, 144.71, 145.24, 145.32, 145.51, 145.78, 146.14, 146.27, 146.46, 147.05, 147.28, 147.36, 149.05, 153.39, 197.77. MALDI TOF, *m/z* 902.075 $[M]^-$ ($C_{73}H_{10}O$).
24. *Methyl 4-[(C$_{60}$-I$_h$)[5,6]fullerene-1(9H)-ylcarbonyl]benzoate (**3**).* IR: 526, 749, 805, 1019, 1107, 1280, 1434, 1457, 1630, 1724 cm$^{-1}$. UV ($CHCl_3$), $\lambda_{max}$, nm: 253, 319, 430. $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 4.03 (s, 3H, $CH_3$), 7.48 (s, 1H, $C_{60}$-H), 8.35 (d, 2H, 2CH, $J$ = 8 Hz), 8.63 (d, 2H, 2CH, $J$ = 8 Hz). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$ 52.47, 57.12, 79.20, 129.21, 130.08, 135.61, 136.23, 136.40, 141.72, 142.24, 142.85, 143.16, 143.41, 144.40, 144.79, 145.49, 145.55, 145.64, 145.87, 146.49, 146.97, 147.49, 147.93, 148.25, 152.03, 165.67, 196.24. MALDI TOF, *m/z* 884.043 $[M]^-$ ($C_{69}H_8O_3$).