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Various α-Oxygen Functionalizations of β-Dicarbonyl Compounds Mediated by the Hypervalent Iodine(III) Reagent *p*-Iodotoluene Difluoride with Different Oxygen-Containing Nucleophiles

Jun Yu,[a] Jun Tian,[a] and Chi Zhang[a,*]

[a] The State Key Laboratory of Elemento-Organic Chemistry, Nankai University, Tianjin 300071, People's Republic of China
Fax: (+86)-22-2349-9247; phone: (+86)-022-2350-9243; e-mail: zhangchi@nankai.edu.cn

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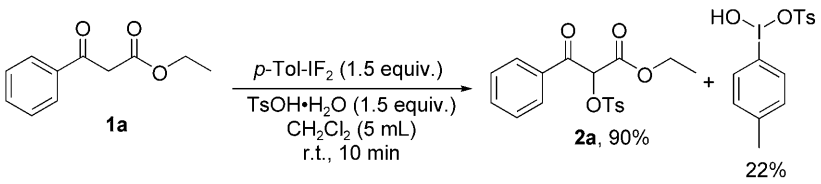
Abstract: *p*-Iodotoluene difluoride (*p*-Tol-IF_2) has been found to be a *general* reagent for the effective introduction of various oxygen-containing functionalities including tosyloxy, mesyloxy, acetoxy, phosphoryloxy, methoxy, ethoxy and isopropoxy at the α-position of β-dicarbonyl compounds. These transformations can be readily realized by the use of the combined reagent of *p*-iodotoluene difluoride and various oxygen-containing nucleophilic compounds such as *p*-toluenesulfonic acid, methanesulfonic acid, acetic acid, diphenyl phosphate, methanol, ethanol and propan-2-ol under mild conditions, respectively. And, the *in situ* generated hypervalent iodine(III) species *via* ligand exchange between *p*-iodotoluene difluoride and the respective oxygen-containing nucleophiles are believed to be the real oxidizing agents in such transformations.

Keywords: β-dicarbonyl compounds; hypervalent compounds; *p*-iodotoluene difluoride; nucleophiles; oxidation

Introduction

The introduction of various oxygen functionalities such as tosyloxy, mesyloxy, acetoxy, phosphoryloxy, methoxy, ethoxy and isopropoxy at the α-position of β-dicarbonyl compounds is an important transformation in organic synthesis since the resulting products are the key intermediates for the synthesis of a variety of heterocyclic[1] and natural products.[2] Methods for the direct α-tosyloxylation of β-dicarbonyl compounds involve the use of various reagents such as *N*-methyl-*O*-tosylhydroxylamine,[3] hydroxy(tosyloxy)-iodobenzene (HTIB)[4,5] and 1-(*p*-toluenesulfonyloxy)-1,2-benziodoxol-3(1*H*)-one.[6] [Hydroxy-(mesyloxy)iodo]benzene (HMIB)[7] is used for the preparation of α-mesyloxylated β-dicarbonyl compounds. Lead tetraacetate[8] and phenyliodine diacetate (PIDA)[9] are usually employed for α-acetoxylation of β-dicarbonyl compounds. (Hydroxy-{[bis(phenyloxy)phosphoryl]oxy}iodo)benzene[10] can be used for the synthesis of α-phosphoryloxylated β-dicarbonyl compounds. In addition, boron trifluoride-etherate activated iodosobenzene has been utilized for the α-methoxylation and ethoxylation of β-dicarbonyl compounds in methanol or ethanol, respectively.[11] To sum up, it is obvious that different oxidizing reagents usually have to be employed for different α-oxygen functionalizations on β-dicarbonyl compounds. Ideally, it would be more convenient to use the same oxidizing reagent with different nucleophiles to realize all the above α-oxygen functionalizations on β-dicarbonyl compounds. However, as far as we know, methods for introducing various oxygen functionalities at the α-position of β-dicarbonyl compounds by using the same oxidant have not been reported. Therefore, it was highly desirable to develop such a *general* and thus convenient method.

(Difluoro)iodoarenes are powerful and selective fluorinating reagents. Using *p*-iodotoluene difluoride (*p*-Tol-IF_2), various β-dicarbonyl compounds,[12] α-(phenylthio)acetamides,[13] α-(phenylthio) esters,[14] α-seleno carboxylic acid derivatives[15] and silyl enol ethers[16] can be selectively fluorinated at the α-position. Alkenes can also be fluorinated with *p*-iodotoluene difluoride to give the rearranged geminal difluorides[17] or *vic*-difluoro products.[18] Also, the phenylselenofluorination[19] and iodofluorination[20] of alkenes can be achieved with the combined reagents *p*-



Scheme 1. α-Tosyloxylation of **1a** with the combined reagent of *p*-Tol-IF_2 and $TsOH{\cdot}H_2O$ in dichloromethane.

Tol-IF_2/PhSeSePh and *p*-Tol-IF_2/I_2, respectively. In addition, (difluoro)iodoarenes are usually involved for the synthesis of various hypervalent iodonium salts.[21] Besides the applications as the fluorinating reagents, (difluoro)iodoarenes can be used as oxidizing reagents as well and there have been some good examples. Koser et al. reported the conversion of silyl enol ethers to tris-ketol phosphates by a mixed reagent of *p*-iodotoluene difluoride and phosphoric acid.[22] Zhdankin et al. developed a convenient procedure for the preparation of 1,4-diketones by the treatment of silyl enol ethers with iodonium species generated *in situ* from (difluoroiodo)benzene and boron trifluoride.[23] In addition, Myers et al. have applied (difluoroiodo)benzene for the oxidation of *N*-*tert*-butyldimethylsilylhydrazones to generate diazoalkanes *in situ* which react with carboxylic acids to form the esters.[24] However, to the best of our knowledge, there is no report on the introduction of oxygen functionalities to the α-position of β-dicarbonyl compounds mediated by (difluoro)iodoarenes. As part of our continuing investigations on oxidation reactions induced by hypervalent iodine reagents,[25] we herein report a *general*, convenient and efficient method for the introduction of various oxygen functionalities including tosyloxy, mesyloxy, acetoxy, phosphoryloxy, methoxy, ethoxy and isopropoxy groups to the α-position of β-dicarbonyl compounds by using *p*-iodotoluene difluoride with different nucleophiles at room temperature.

Results and Discussion

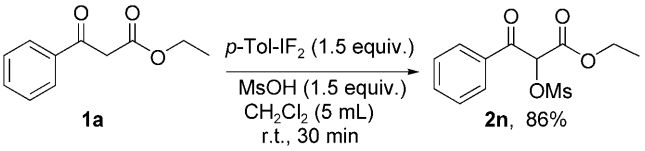
The Combination of *p*-Iodotoluene Difluoride with Organic Acids

α-Tosyloxylation of β-Dicarbonyl Compounds with the Combined Reagent of *p*-Iodotoluene Difluoride and *p*-Toluenesulfonic Acid Monohydrate in Dichloromethane

Initially, ethyl benzoylacetate (**1a**) (1 mmol) was chosen as the model substrate to react with 1.5 equivalents of *p*-iodotoluene difluoride and 3.0 equivalents of *p*-toluenesulfonic acid monohydrate in 5 mL of dichloromethane at room temperature. After 10 min, it was interesting to find that the corresponding α-tosyloxylated product ethyl α-tosyloxybenzoylacetate (**2a**) was obtained in 94% yield together with the formation of 4-[hydroxy(tosyloxy)iodo]toluene in 15% yield (based on the amount of *p*-iodotoluene difluoride). Importantly, when a decreased amount of *p*-toluenesulfonic acid monohydrate (1.5 equivalents) was used, the reaction gave a similar result and a 22% yield of 4-[hydroxy(tosyloxy)iodo]toluene was obtained (Scheme 1).

To demonstrate the generality of this method, the scope of the reaction was investigated and the results are summarized in Table 1. It was found that the reaction conditions shown in Scheme 1 were suitable for a range of β-keto esters, β-diketones and a β-ketoamide all of which went to completion within 10 min. For reactions of β-keto esters, both aromatic and aliphatic ones gave the corresponding α-tosyloxylated products in high to excellent yields (Table 1, entries 1–9). As for β-diketones **1j**, **1k** and **1l**, the reactions also provided the desired products **2j**, **2k** and **2l** in high to excellent yields (entries 10–12). Similarly, a β-ketoamide *N*,*N*-dimethyl-3-oxobutanamide (**1m**) was also smoothly α-tosyloxylated to yield the expected product 1-(dimethylamino)-1,3-dioxobutan-2-yl 4-methylbenzenesulfonate (**2m**) in 94% yield (entry 13).

Not surprisingly, α-mesyloxylation also worked on the substrate **1a** by using the combined reagent of *p*-iodotoluene difluoride and methanesulfonic acid (Scheme 2).

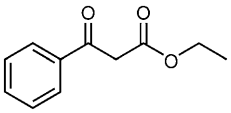
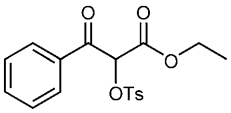
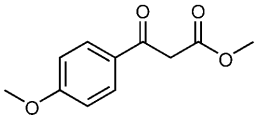
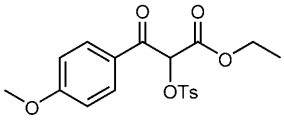
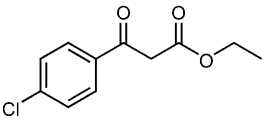
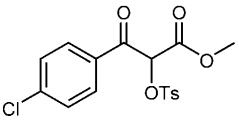
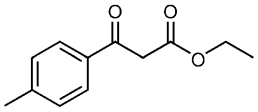
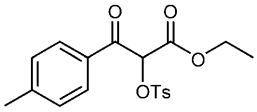
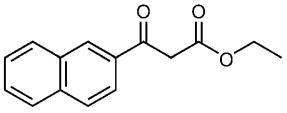
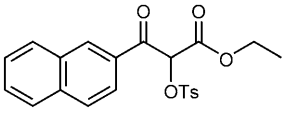
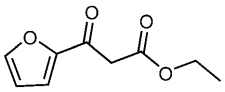
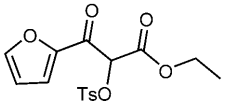
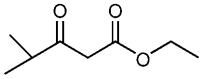
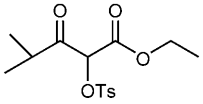
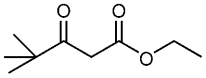
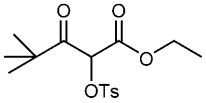
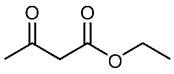
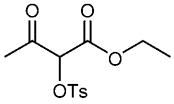
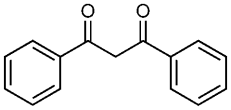
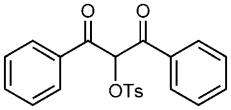
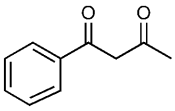
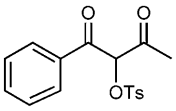
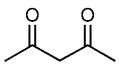
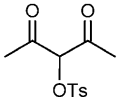
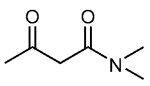
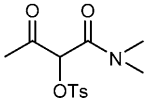


Scheme 2. α-Mesyloxylation of ethyl benzoylacetate (**1a**) with the combined reagent of *p*-Tol-IF_2 and MsOH in dichloromethane.

α-Acetoxylation of β-Dicarbonyl Compounds with the Combined Reagent of *p*-Iodotoluene Difluoride and Acetic Acid in Dichloromethane

With the same oxidizing agent *p*-iodotoluene difluoride, the α-acetoxylation of β-dicarbonyl compounds can be realized as well. In a preliminary experiment, ethyl benzoylacetate (**1a**) was treated with 1.5 equiva-

Table 1. α-Tosyloxylation of β-dicarbonyl compounds with the combined reagent of *p*-Tol-IF_2 and $TsOH{\cdot}H_2O$ in dichloromethane.[a,b]

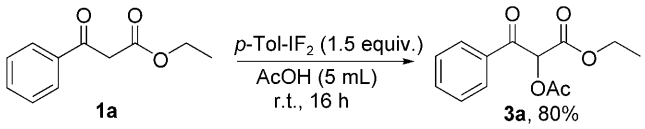
Entry	Substrate		Product		Time [min]	Yield [%][c]
1	**1a**		**2a**		10	90[d]
2	**1b**		**2b**		5	94
3	**1c**		**2c**		5	93
4	**1d**		**2d**		5	93
5	**1e**		**2e**		10	91
6	**1f**		**2f**		10	86
7	**1g**		**2g**		5	85
8	**1h**		**2h**		5	98
9	**1i**		**2i**		5	91
10	**1j**		**2j**		5	91
11	**1k**		**2k**		5	85
12	**1l**		**2l**		5	82
13	**1m**		**2m**		5	94

[a] Reactions were conducted with 1 mmol of β-dicarbonyl compounds under the conditions shown in Scheme 1.
[b] 4-[Hydroxy(tosyloxy)iodo]toluene was obtained in the yield range of 6-22% except for substrate **1m**.
[c] Isolated yield.
[d] 1% of ethyl 2-fluoro-3-oxo-3-phenylpropionate was detected.

lents of *p*-iodotoluene difluoride in 5 mL of acetic acid at room temperature. It was encouraging to observe the formation of ethyl 2-acetoxy-3-oxo-3-phenylpropanoate (**3a**) in 80% yield although the reaction proceeded slowly (16 h) (Scheme 3).

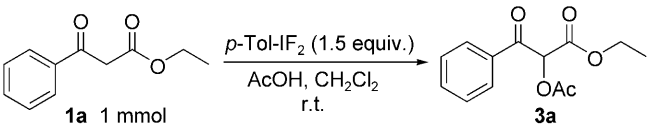
In order to improve the efficiency of the reaction and simplify its work-up, the reaction conditions were optimized *via* introduing dichloromethane as the solvent and subsequently changing the volume ratio of acetic acid and dichloromethane (Table 2). Firstly, substrate **1a** was subjected to 1.5 equivalents of *p*-iodotoluene difluoride and acetic acid (0.172 mL, 3.0 equivalents) in 5 mL of dichloromethane. It was found that the reaction was completed in a shorter time (4 h) but afforded a lower yield of **3a** (60%) (Table 2, entry 2). When 1 mL of acetic acid was employed (17.5 equivalents), the reaction was completed in 1.5 h and the yield of **3a** was improved to 72% (entry 3). Increasing the amount of acetic acid up to 3 mL (52.5 equivalents) resulted in a complete reaction within 50 min and an excellent yield of **3a** (entry 5).

With the optimized conditions in hand, we investigated the substrate generality of this method and the results are shown in Table 3. The ethyl benzoylacetate derivatives bearing either electron-donating groups or electron-withdrawing groups on the phenyl rings **1b**, **1c** and **1d** afforded excellent results (Table 3, entries 2–4). Other β-keto esters were also efficiently transformed to their corresponding α-acetoxylated products in high yields (entries 5–9). Two β-diketones **1j** and **1k** also reacted smoothly under the optimized conditions to provide the desired α-acetoxylated β-diketones **3j** and **3k** in high yields within short reaction times (entries 10 and 11). This method can be successfully extended to a β-ketoamide **1m** as well (entry 12).



Scheme 3. α-Acetoxylation of **1a** with *p*-Tol-IF_2 in AcOH.

Table 2. Optimization of the reaction conditions of α-acetoxylation on **1a**.



Entry	$AcOH/CH_2Cl_2$ [mL/mL]	Time [h]	Yield [%][a]
1	5/0	16	80
2	0.172/5	4	60
3	1/5	1.5	72
4	2/5	1	84
5	3/5	50 min	94

[a] Isolated yield.

α-Phosphoryloxylation of β-Dicarbonyl Compounds with the Combined Reagent of *p*-Iodotoluene Difluoride and Diphenyl Phosphate in Dichloromethane

p-Iodotoluene difluoride could also be utilized for the α-phosphoryloxylation of β-dicarbonyl compounds (Table 4). When **1a** was subjected to 1.5 equivalents of *p*-iodotoluene difluoride and 3.0 equivalents of diphenyl phosphate in 5 mL of dichloromethane at room temperature, the reaction provided the corresponding α-phosphoryloxylated product **4a** in 86% yield within 15 min (Table 4, entry 1). Under the same conditions, a β-diketone **1j** and a β-ketoamide **1m** could also be smoothly converted to their corresponding α-phosphoryloxylated products **4j** and **4m** in good yields, respectively (entries 2 and 3).

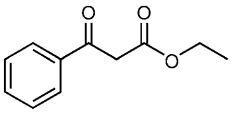
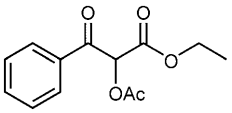
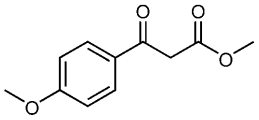
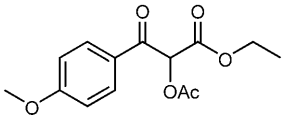
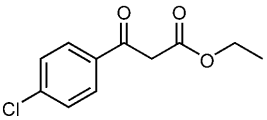
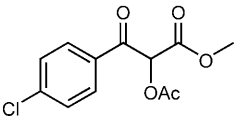
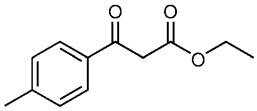
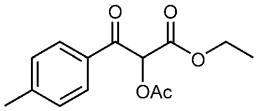
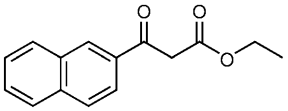
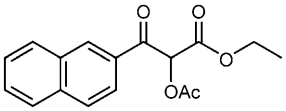
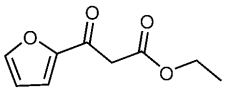
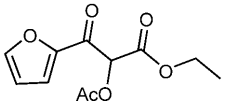
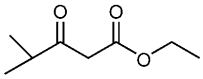
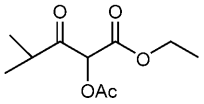
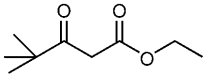
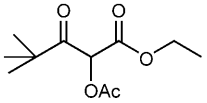
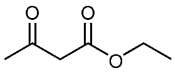
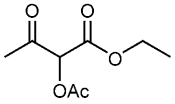
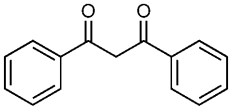
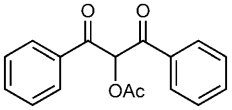
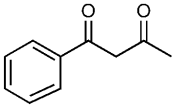
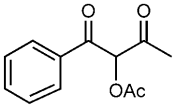
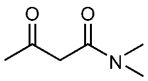
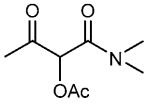
The Combination of *p*-Iodotoluene Difluoride with Alcohols

α-Methoxylation of β-Dicarbonyl Compounds with *p*-Iodotoluene Difluoride in Methanol

We also examined whether *p*-iodotoluene difluoride would be effective for the α-methoxylation of β-dicarbonyl compounds. To our delight, the reaction of **1a** with 1.5 equivalents of *p*-iodotoluene difluoride in 5 mL of methanol was completed in 4 h at room temperature to afford ethyl 2-methoxy-3-oxo-3-phenylpropanoate (**5a)** in 83% yield (Scheme 4).

A variety of β-dicarbonyl compounds including β-keto esters, β-diketones and a β-ketoamide were tested using this new α-methoxylation protocol (Table 5). The *para*-substituted ethyl benzoylacetates **1b**, **1c**, **1d** were smoothly converted to their corresponding α-methoxylated products **5b**, **5c** and **5d** in high yields within 4 h (Table 5, entries 2–4). Other aromatic ring systems such as naphthalene and furan were well tolerared as indicated by the successful transformation of substrates **1e** and **1f** (entries 5 and 6). Methyl 1-oxo-2-indanecarboxylate (**1n**) can also be readily oxidized to the corresponding α-methoxylated product **5n** in an excellent yield (entry 7). In the case of ethyl 3-oxo-3-(pyridin-2-yl)propanoate (**1o**), the mono-methoxylated product **5o** was obtained in 50% yield together with formation of the dimethoxylated product in 29% yield (entry 8). As for aliphatic β-keto esters **1g**, **1h** and **1p**, their corresponding α-methoxylated products **5g**, **5h** and **5p** were obtained in

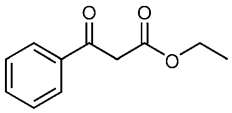
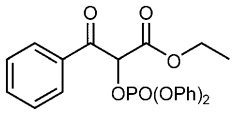
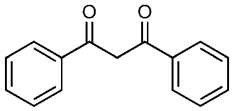
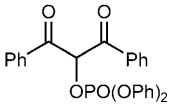
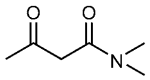
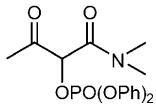
Table 3. α-Acetoxylation of β-dicarbonyl compounds with the combined reagent of *p*-Tol-IF_2 and AcOH in dichloromethane.[a]

Entry	Substrate		Product		Time [min]	Yield [%][b]
1	**1a**		**3a**		50	94
2	**1b**		**3b**		20	93
3	**1c**		**3c**		35	88
4	**1d**		**3d**		75	90
5	**1e**		**3e**		35	80
6	**1f**		**3f**		30	80
7	**1g**		**3g**		60	78
8	**1h**		**3h**		80	85
9	**1i**		**3i**		60	70
10	**1j**		**3j**		15	81
11	**1k**		**3k**		20	70
12	**1m**		**3m**		30	75

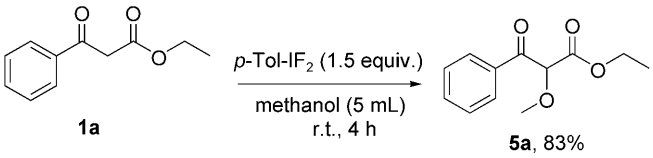
[a] Reactions were conducted with 1 mmol of β-dicarbonyl compounds, 1.5 mmol of *p*-Tol-IF_2 in 3 mL of AcOH and 5 mL of dichloromethane at room temperature.
[b] Isolated yield.

high yields (entries 9-11). Two β-diketones **1j** and **1k** were also smoothly α-methoxylated to give **5j** and **5k** in high yields, respectively (entries 12 and 13). Notably, three equivalents of methanol were enough for the completion of these two reactions. A β-ketoamide, *N,N*-dimethyl-3-oxobutanamide (**1m**), was examined as well and the reaction afforded the expected α-methoxylated product **5m** in an excellent yield within 1 h (entry 14).

Table 4. α-Phosphoryloxylation of β-dicarbonyl compounds with the combined reagent of *p*-iodotoluene difluoride and diphenyl phosphate in dichloromethane.[a]

Entry		Substrate		Product	Time [min]	Yield [%][b]
1	**1a**		**4a**		15	86[c]
2	**1j**		**4j**		20	66
3	**1m**		**4m**		20	75

[a] Reactions were conducted with 1 mmol of β-dicarbonyl compounds, 1.5 mmol of *p*-iodotoluene difluoride and 3.0 mmol of diphenyl phosphate in 5 mL of dichloromethane at room temperature.
[b] Isolated yield.
[c] 1% of ethyl 2-fluoro-3-oxo-3-phenylpropionate was detected.



Scheme 4. α-Methoxylation of **1a** with *p*-Tol-IF_2 in methanol.

Ethoxylation and Isopropoxylation of 1a with *p*-Iodotoluene Difluoride in Ethanol or 2-Propanol

The ethoxylation was also tried still using **1a** as the substrate and it was found that the use of ethanol as the solvent could successfully lead to the formation of the corresponding α-ethoxylated product (**5q**) in high yield (Scheme 5). However, as for isopropoxylation,

Table 5. α-Methoxylation of β-dicarbonyl compounds with *p*-Tol-IF_2 in methanol.[a]

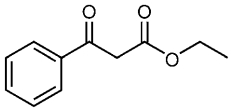
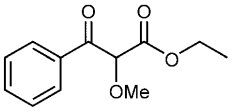
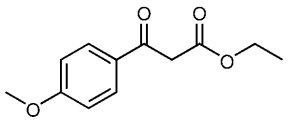
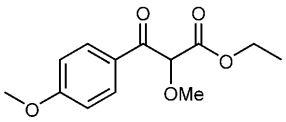
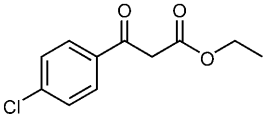
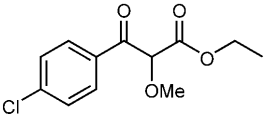
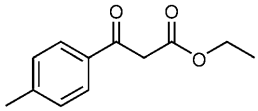
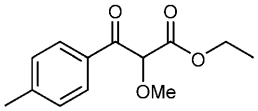
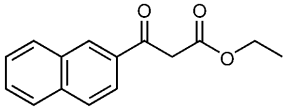
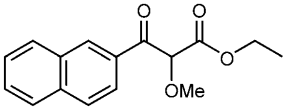
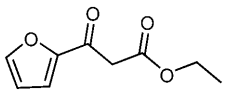
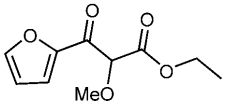
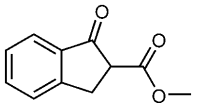
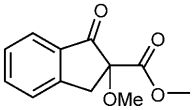
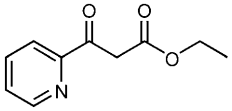
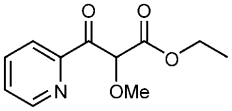
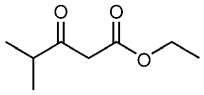
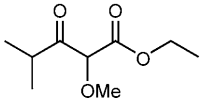
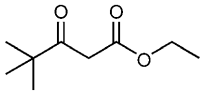
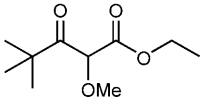
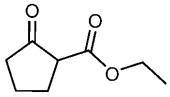
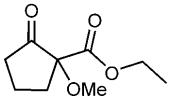
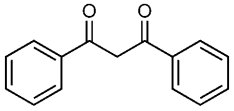
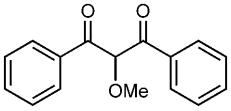
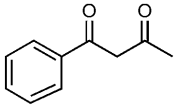
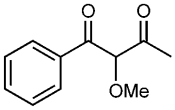
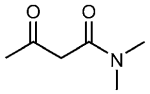
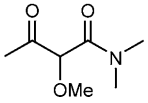
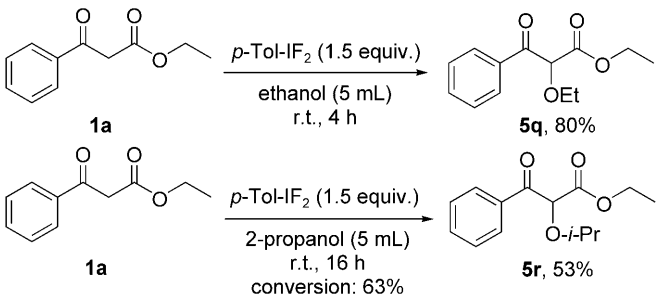
Entry		Substrate		Product	Time [h]	Yeld [%][b]
1	**1a**		**5a**		4	83[c]
2	**1b**		**5b**		4	87
3	**1c**		**5c**		4	83
4	**1d**		**5d**		4	89
5	**1e**		**5e**		11	80
6	**1f**		**5f**		1	88

Table 5. (Continued)

Entry		Substrate		Product	Time [h]	Yeld [%][b]
7	**1n**		**5n**		4	91
8	**1o**		**5o**		4	50[d]
9	**1g**		**5g**		4	70[e]
10	**1h**		**5h**		24	70
11	**1p**		**5p**		4	81
12	**1j**		**5j**		0.5	75[f]
13	**1k**		**5k**		5	72[f]
14	**1m**		**5m**		1	90

[a] Unless otherwise indicated, the reactions were conducted with 1 mmol of β-dicarbonyl compounds under the conditions shown in Scheme 4.
[b] Isolated yield.
[c] 2% of ethyl 2-fluoro-3-oxo-3-phenylpropionate was detected.
[d] The α-dimethoxylated product was obtained in 29% yield.
[e] GC yield.
[f] The reaction was carried out with 1 mmol of β-diketone, 1.5 mmol of *p*-iodotoluene difluoride and 3.0 mmol of methanol in 5 mL of dichloromethane at room temperature.

the desired α-isopropoxylated product (**5r)** was obtained in a moderate yield (53%) with the conversion of starting material being 63% even after 16 h. This is largely the consequence of the bulkiness of 2-propanol compared with that of methanol and ethanol.

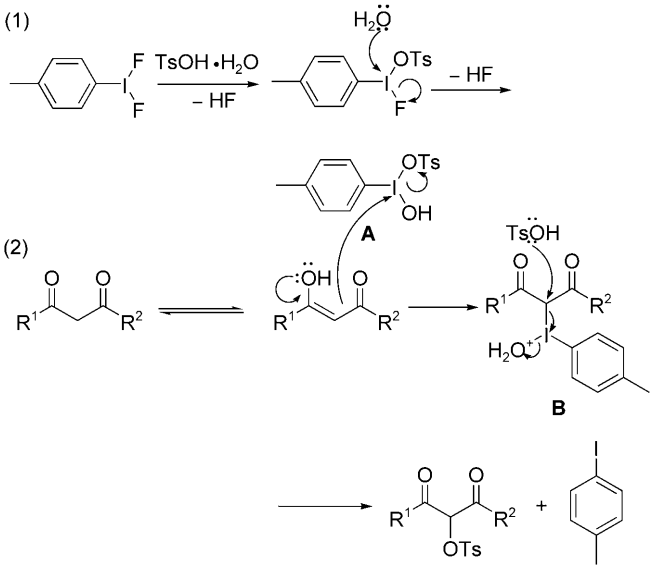


Scheme 5. The ethoxylation and isopropoxylation of **1a** with *p*-iodotoluene difluoride in ethanol or 2-propanol.

Mechanism Considerations

The Mechanism of *p*-Iodotoluene Difluoride-Mediated α-Tosyloxylation, Acetoxylation and Phosphoryloxylation of β-Dicarbonyl Compounds

The mechanism of our new α-tosyloxylation reactions is outlined in Scheme 6. The isolation of 4-[hydroxy-(tosyloxy)iodo]toluene in the synthesis of α-tosyloxylated β-dicarbonyl compounds indicated that two steps were involved in our tosyloxylation reaction.

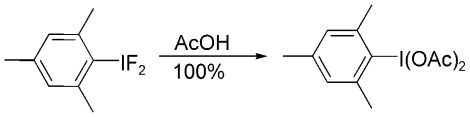


Scheme 6. Plausible mechanism of *p*-iodotoluene difluoride mediated α-tosyloxylation of β-dicarbonyl compounds.

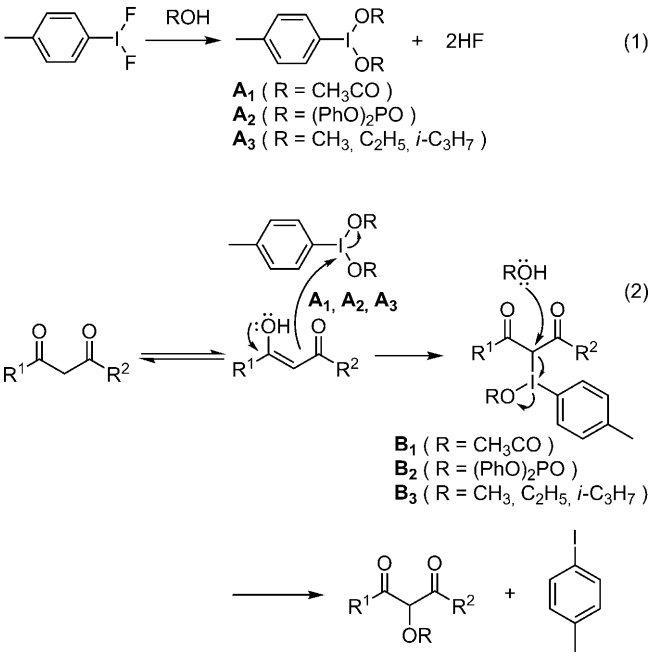
Firstly, *p*-iodotoluene difluoride reacted with *p*-toluenesulfonic acid monohydrate to produce 4-[hydroxy(tosyloxy)iodo]toluene (**A**) and hydrofluoric acid[26] which promoted the formation of the enol form of the β-dicarbonyl compounds. Then, electrophilic addition of **A** to the enol form of the β-dicarbonyl compounds gave the intermediate **B** which was followed by the nucleophilic attack of TsOH upon the α-carbon-bearing iodine(III) structural unit in **B** to yield the corresponding α-tosyloxylated products with the concomitant reductive elimination of *p*-iodotoluene[4]. In our initial procedure, ethyl benzoylacetate (**1a**) was converted to ethyl α-tosyloxybenzoylacetate (**2a**) in 94% yield within 10 min by using 1.5 equivalents of *p*-iodotoluene difluoride and 3.0 equivalents of $TsOH{\cdot}H_2O$. However, according to the first step of the mechanism shown in Scheme 6 in which the nuclephilic attack of water was considered, a 1:1 mixture of $TsOH{\cdot}H_2O$ and *p*-iodotoluene difluoride should be enough to produce the intermediate **A**. Therefore, 1.5 equivalents of $TsOH{\cdot}H_2O$ were employed and the reaction proceeded well as expected (Scheme 1 and Table 1).

Shreeve et al. have reported that 2-difluoroiodo-1,3,5-trimethylbenzene could be quickly converted into its diacetate in quantitative yield when treated with acetic acid (Scheme 7).[26,27] Thus, in our new α-acetoxylation reactions, a similar ligand exchange reaction between *p*-iodotoluene difluoride and acetic acid should be involved to generate the active intermediate $\mathbf{A_1}$ shown in Scheme 8. Then, the intermediate $\mathbf{A_1}$ oxidized the enol form of the β-dicarbonyl compounds to provide the corresponding α-acetoxylated products *via* the intermediate $\mathbf{B_1}$ (Scheme 8).[9]

Several experiments were carried out to probe the reactive intermediate of our α-phosphoryloxylation reaction. *p*-Iodotoluene difluoride was mixed with 2.0 equivalents of diphenyl phosphate in $CDCl_3$ and monitored by ^1H NMR and ^{31}P NMR spectroscopy. The ^1H NMR spectrum of the mixture revealed that *p*-iodotoluene difluoride was consumed after 15 min and a new compound was formed which was believed to be *p*-$CH_3C_6H_4I(OPO(OPh)_2)_2$ ($\mathbf{A_2}$) on the basis of its ^1H NMR spectrum (Figure 1). The ^{31}P NMR spectrum suggested the change of diphenyl phosphate and the formation of a new compound since the signal of diphenyl phosphate (−10.58 ppm) disappeared and a new signal appeared at −11.89 ppm (Figure 2). The mass spectrum for the reaction mixture of *p*-iodotoluene difluoride (1 mmol) and diphenyl phosphate (2.0 mmol) in 5 mL of dichloromethane showed that a peak appeared at $m/z = 717$ (Figure 3), corresponding to $[M+H]^+$ (molecular weight of $\mathbf{A_2}$: 716). All these results indicated the presence of $\mathbf{A_2}$, which acted as the real oxidizing reagent in our phosphoryloxylation reaction (Scheme 8).



Scheme 7. Ligand exchange reaction between 2-difluoroiodo-1,3,5-trimethylbenzene and AcOH.



Scheme 8. Plausible mechanism of *p*-iodotoluene difluoride mediated α-acetoxylation, phosphoryloxylation and alkoxylation of β-dicarbonyl compounds.

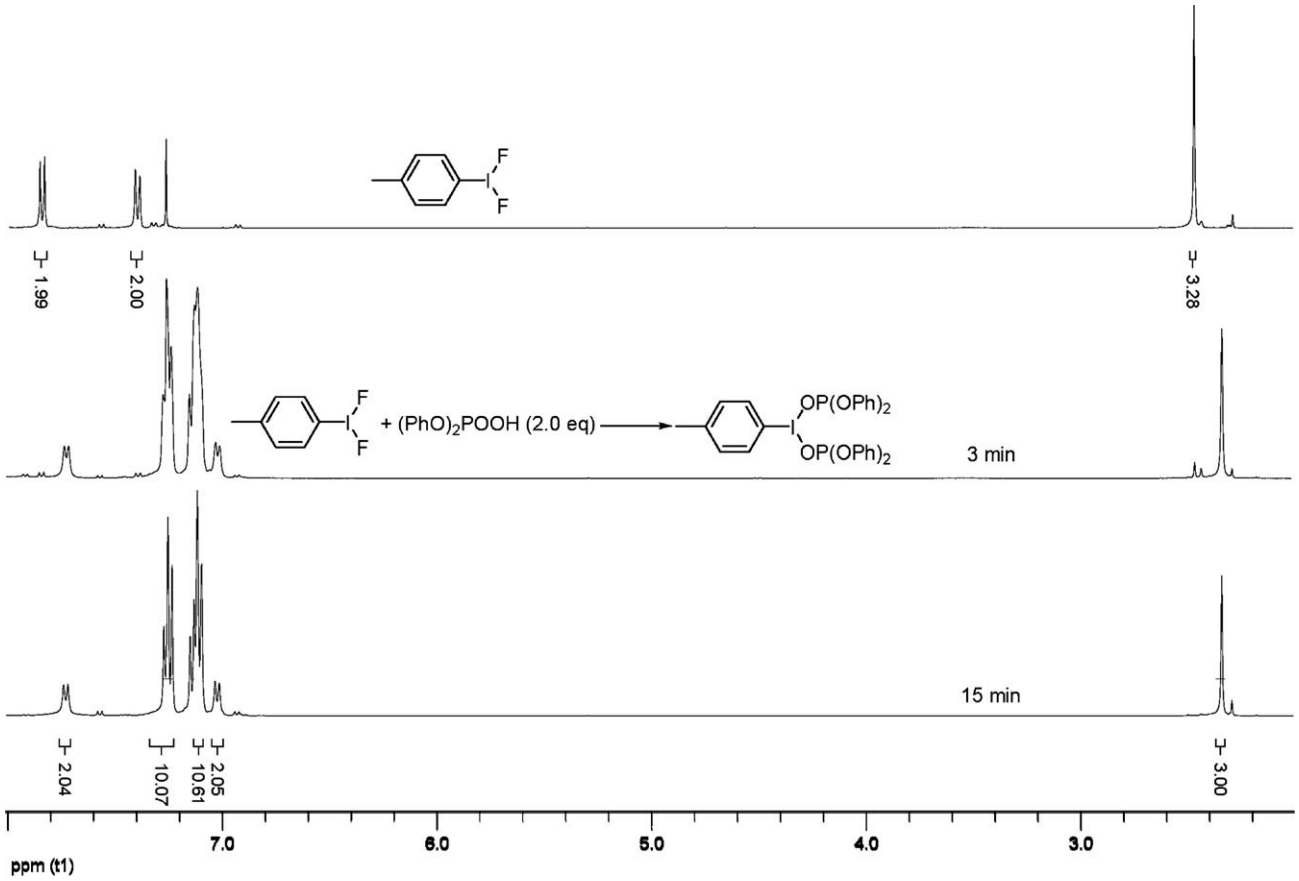


Figure 1. ^{1}H NMR spectrum (400 MHz) of *p*-iodotoluene difluoride (*top*) and that of the reaction mixture of *p*-iodotoluene difluoride (0.05 mmol) and diphenyl phosphate (0.1 mmol) in 1 mL of $CDCl_3$ after 3 min (*middle*) and 15 min (*bottom*), respectively.

The Mechanism of *p*-Iodotoluene Difluoride-Mediated α-Alkoxylation of β-Dicarbonyl Compounds

Moriarty et al. have reported that boron trifluoride-etherate activated iodosobenzene could be utilized for the α-alkoxylation of β-dicarbonyl compounds in alcohols.[11] Here, the *in situ* generated alkoxyiodine-(III) reagents $PhI(OR)_2$ (R = Me, Et) were believed to be the key intermediates of these transformations.[11,28] Thus, the mechanism of our α-alkoxylation reaction was also believed to involve an initial ligand exchange reaction between *p*-iodotoluene difluoride and alcohols to generate the alkoxyiodine(III) intermediates *p*-$CH_3C_6H_4I(OR)_2$ (**A_3**). Then, the intermediate **A_3** oxidized the enol form of the β-dicarbonyl compounds to yield the corresponding α-alkoxylated products *via* the intermediate **B_3** (Scheme 8).

Conclusions

The reported hypervalent iodine reagent, *p*-iodotoluene difluoride, was found to effect the introduction of various oxygen functionalities including tosyloxy, mesyloxy, acetoxy, phosphoryloxy, methoxy, ethoxy and isopropoxy to the α-position of β-dicarbonyl compounds. It is significant that all these transformations were accomplished by using the same reagent *p*-iodotoluene difluoride, which is readily available. In addition, these reactions are tolerant of a range of functional groups and thus effective for a broad scope of substrate. The *in situ* generated active hypervalent iodine species are believed to be the real oxidizing agent in these reactions. Considering the *generality*, convenience and efficiency of the present method, it should be an attractive method to synthesize various α-oxygen functionalized β-dicarbonyl compounds.

Experimental Section

Materials and Methods

p-Iodotoluene difluoride was prepared according to the reported method.[14b] Alcohols, acetic acid, *p*-toluenesulfonic acid monohydrate, methanesulfonic acid and diphenyl phosphate were purchased from commercial suppliers. The

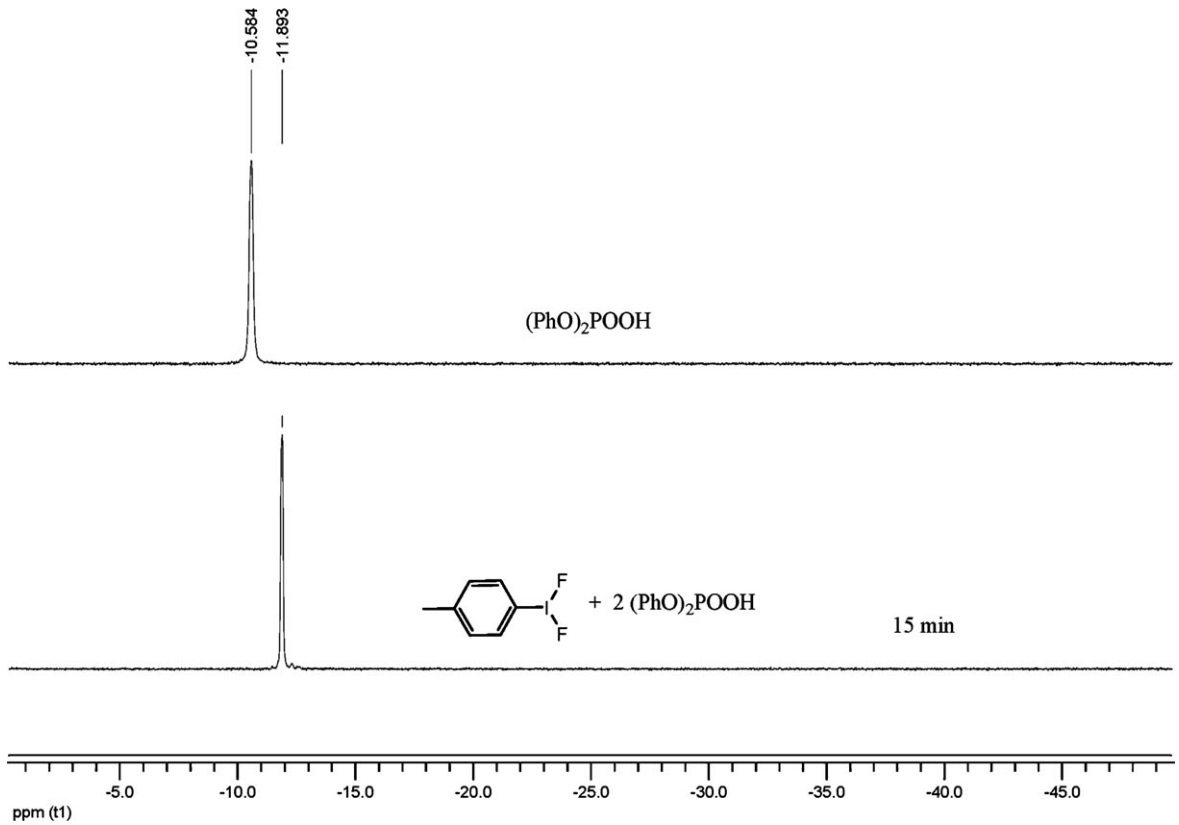


Figure 2. ^{31}P NMR spectrum (121 MHz) of diphenyl phosphate (*top*) and that of the mixture of *p*-iodotoluene difluoride (0.05 mmol) and diphenyl phosphate (0.1 mmol) in 1 mL of $CDCl_3$ after 15 min (*bottom*).

^{1}H NMR spectra were recorded at 400 MHz and ^{13}C NMR spectra were measured at 100 MHz using a Bruker AV400 instrument with $CDCl_3$ or DMSO-d_6 as the solvent. The ^{19}F NMR spectrum was recorded at 376 MHz and ^{31}P NMR spectra were measured at 121 MHz still using a Bruker AV400 instrument with $CDCl_3$ as the solvent. IR spectra were recorded on a FT-IR Bruker EQUINOX55 spectrometer in KBr pellets. High resolution mass spectral analyses (HR-MS) were performed on a high resolution ESI-FTICR or MALDI-FTICR mass spectrometer (Varian 7.0 T). MS-APCI data were colleted using a ThermoFisher Scientific mass spectrometer system (Surveyor MSQ Plus). GC analyses were carried out on a Shimadzu 2014 series GC system equipped with an Rtx-5 column (30 m, ID 0.25 mm) and an FID. Petroleum ether (PE), where used, had the boiling point range 60–90 °C.

Typical Procedure for α-Tosyloxylation of β-Dicarbonyl Compounds

To a solution of ethyl benzoylacetate (**1a**) (192 mg, 1 mmol) in 5 mL of dichloromethane in a 10-mL round-bottom flask were added *p*-toluenesulfonic acid monohydrate (285 mg, 1.5 mmol) and *p*-iodotoluene difluoride (384 mg, 1.5 mmol). The reaction mixture was stirred at room temperature and monitored by TLC. After 10 min, the white solid was collected by filtration and washed with 20 mL of dichloromethane to afford 4-[hydroxy(tosyloxy)iodo]toluene; yield: 135 mg. The filtrate was washed with saturated aqueous $NaHCO_3$ (5 mL) and saturated aqueous $Na_2S_2O_3$ (5 mL). The separated aqueous phase was extracted with dichloromethane (20 mL). The combined organic layer was washed with brine, dried over anhydrous Na_2SO_4 and concentrated in vacuo to afford the crude product which was purified by flash column chromatograpy (PE-EtOAc, 17:3) to give **2a** as a colorless oil; yield: 326 mg (90%).[4a] ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 1.17$ (t, $J = 7.2$ Hz, 3H), 2.43 (s, 3H), 4.14–4.22 (m, 2H), 5.99 (s, 1H), 7.29 (t, $J = 8.0$ Hz, 2H), 7.46 (t, $J = 8.0$ Hz, 2H), 7.61(t, $J = 8.0$ Hz, 1H), 7.79 (d, $J = 8.0$ Hz, 2H), 7.92 (d, $J = 8.0$ Hz, 2H); ^{13}C NMR (100 MHz): $\delta = 13.79$, 21.67, 62.83, 78.06, 128.29, 128.73, 129.39, 129.83, 132.40, 133.30, 134.37, 145.65, 164.15, 188.20.

4-[Hydroxy(tosyloxy)iodo]toluene:[26] White solid, mp:137–138 °C. ^{1}H NMR (400 MHz, DMSO-d_6): $\delta = 2.26$ (s, 3H), 2.38 (s, 3H), 7.09 (d, $J = 7.6$ Hz, 2H), 7.37 (d, $J = 7.6$ Hz, 2H), 7.45 (d, $J = 7.6$ Hz, 2H), 8.06 (d, $J = 7.6$ Hz, 2H), 9.63 (bs, 1H); ^{13}C NMR (100 MHz, DMSO-d_6): $\delta =$ 22.10, 22.33, 121.65, 126.82, 129.49, 132.94, 136.06, 139.35, 144.25, 146.30.

Ethyl 2-fluoro-3-oxo-3-phenylpropionate:[12c] Colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 1.26$ (t, $J = 7.2$ Hz, 3H), 4.27–4.33 (m, 2H), 5.87 (d, $J = 48.8$ Hz, 1H), 7.50 (t, $J = 7.2$ Hz, 2H), 7.64 (t, $J = 7.2$ Hz, 1H), 8.04 (d, $J = 8.4$ Hz, 2H); ^{13}C NMR (100 MHz): $\delta = 13.92$, 62.69, 90.08 (d, $J =$ 196.5 Hz), 128.81, 129.49, 133.36, 134.51, 164.90 (d, $J =$ 23.8 Hz), 189.53 (d, $J = 20.2$ Hz); ^{19}F NMR (376 MHz): $\delta =$ −190.32.

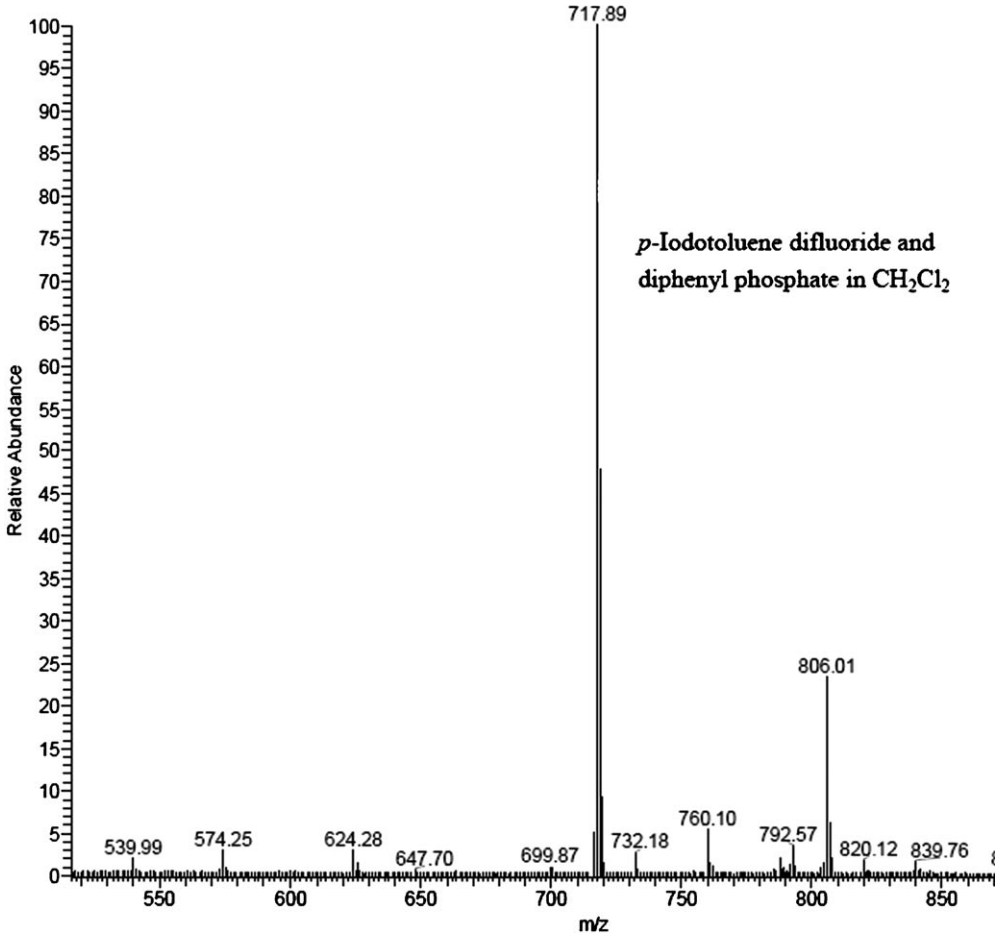


Figure 3. The mass spectrum (APCI) of the reaction mixture of *p*-iodotoluene difluoride (1 mmol) and diphenyl phosphate (2.0 mmol) in 5 mL of dichloromethane.

Ethyl 3-(4-methoxyphenyl)-3-oxo-2-(tosyloxy)propanoate (2b): White solid, mp: 88–90 °C. IR (KBr): ν = 3434, 3012, 2988, 2962, 2841, 1766, 1753, 1676, 1599, 1515, 1463, 1366, 1340, 1329, 1310, 1272, 1244, 1203, 1192, 1123, 1038, 897, 830, 813, 847, 798, 738, 723, 687, 654, 643, 586, 556, 525 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.17$ (t, $J =$ 7.2 Hz, 3H), 2.42 (s, 3H), 3.87 (s, 3H), 4.12–4.21 (m, 2H), 5.94 (s, 1H), 6.92 (d, $J = 8.4$ Hz, 2H), 7.30 (d, $J = 8.4$ Hz, 2H), 7.79 (d, $J = 8.4$ Hz, 2H), 7.93(d, $J = 8.4$ Hz, 2H); ^{13}C NMR (100 MHz): $\delta = 13.82$, 21.67, 55.57, 62.71, 78.07, 114.02, 126.23, 128.29, 129.80, 131.97, 132.51, 145.57, 164.43, 164.53, 186.37; HR-MS (ESI): $m/z = 415.0817$, calcd. for $C_{19}H_{20}O_7SNa$ $[M+Na]^+$: 415.0822.

Ethyl 3-(4-chlorophenyl)-3-oxo-2-(tosyloxy)propanoate (2c): White solid, mp 73–75 °C. IR (KBr): ν = 3501, 3431, 3378, 3094, 2991, 2945, 2925, 2908, 1760, 1698, 1590, 1572, 1490, 1474, 1403, 1366, 1360, 1343, 1312, 1294, 1232, 1205, 1176, 1115, 1095, 1041, 1010, 927, 895, 827, 816, 711, 683, 569, 540 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.17$ (t, $J =$ 7.2 Hz, 3H), 2.43 (s, 3H), 4.13–4.22 (m, 2H), 5.91 (s, 1H), 7.30 (d, $J = 8.4$ Hz, 2H), 7.42 (d, $J = 8.4$ Hz, 2H), 7.70 (d, $J =$ 8.4 Hz, 2H), 7.87 (d, $J = 8.4$ Hz, 2H); ^{13}C NMR (100 MHz): $\delta = 13.77$, 21.66, 62.95, 78.12, 128.25, 129.09, 129.86, 130.78, 131.54, 132.19, 141.02, 145.80, 163.92, 187.20; HR-MS (ESI): *m/z:* 397.0505, calcd. for $C_{18}H_{17}O_6SCl$ $[M+H]^+$: 397.0507.

Ethyl 3-oxo-3-*p*-tolyl-2-(tosyloxy)propanoate (2d): Colorless oil. IR (KBr): ν = 3036, 2983, 2926, 1766, 1693, 1606, 1573, 1447, 1409, 1372, 1294, 1235, 1177, 1191, 1122, 1096, 1060, 1041, 963, 898, 813, 791, 750, 713, 678, 553, 473 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.10$ (t, $J = 7.2$ Hz, 3H), 2.34 (s, 3H), 2.36 (s, 3H), 4.08–4.14 (m, 2H), 5.89 (s, 1H), 7.18 (d, $J = 8.0$ Hz, 2H), 7.23 (d, $J = 8.0$ Hz, 2H), 7.72 (d, $J =$ 8.0 Hz, 2H), 7.76 (d, $J = 8.0$ Hz, 2H); ^{13}C NMR (100 MHz): $\delta = 13.80$, 21.67, 21.79, 62.75, 78.03, 128.29, 129.46, 129.55, 129.80, 130.84, 132.50, 145.59, 145.62, 164.30, 187.66; HR-MS (ESI): $m/z = 399.0869$, calcd. for $C_{19}H_{20}O_6SNa$ $[M+Na]^+$: 399.0873.

Ethyl 3-(naphthalen-2-yl)-3-oxo-2-(tosyloxy)propanoate (2e): Colorless oil. IR (KBr): ν = 3061, 2983, 2939, 1766, 1690, 1626, 1597, 1469, 1372, 1293, 1226, 1192, 1178, 1125, 1095, 1047, 1021, 978, 935, 912, 864, 813, 767, 751, 706, 692, 661, 552, 476 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.18$ (t, $J = 7.2$ Hz, 3H), 2.39 (s, 3H), 4.16–4.25 (m, 2H), 6.13 (s, 1H), 7.24 (s, 1H), 7.26 (s, 1H), 7.57 (t, $J = 8.0$ Hz, 1H), 7.64 (t, $J = 8.0$ Hz, 1H), 7.79 (d, $J = 8.0$ Hz, 2H), 7.87 (d, $J =$ 8.0 Hz, 2H), 7.93 (t, $J = 8.0$ Hz, 2H), 8.49 (s, 1H); ^{13}C NMR (100 MHz): $\delta = 13.89$, 21.70, 62.92, 78.15, 124.16, 127.11, 127.81, 128.33, 128.72, 129.43, 129.87, 130.02, 130.68, 132.06, 132.23, 132.49, 136.03, 145.70, 164.35, 188.14; HR-MS (ESI): $m/z = 413.1054$, calcd. for $C_{22}H_{20}O_6SNa$ $[M+H]^+$: 413.1053.

Ethyl 3-(furan-2-yl)-3-oxo-2-(tosyloxy)propanoate (2f): Light red oil. IR (KBr): ν = 3328, 3131, 2980, 2935, 1770, 1747, 1681, 1634, 1597, 1572, 1494, 1463, 1399, 1371, 1295, 1262, 1178, 1122, 1095, 1067, 1031, 993, 930, 881, 815, 790, 742, 688, 664, 592, 555, 536 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.18$ (t, $J = 7.2$ Hz, 3H), 2.44 (s, 3H), 4.13–4.22 (m, 2H), 5.83 (s, 1H), 6.59 (dd, $J = 1.6$ Hz, 3.6 Hz, 1H), 7.33 (d, $J = 8.4$ Hz, 2H), 7.44 (t, $J = 3.6$ Hz, 1H), 7.65 (s, 1H), 7.82 (d, $J = 8.4$ Hz, 2H); ^{13}C NMR (100 MHz): $\delta = 13.81$, 21.70, 62.88, 112.97, 121.54, 128.30, 129.85, 132.40, 145.69, 148.29, 149.32, 163.69, 176.13; HR-MS (ESI): $m/z =$ 375.0504, calcd. for $C_{16}H_{16}O_7SNa$ $[M+Na]^+$: 375.0509.

Ethyl 4-methyl-3-oxo-2-(tosyloxy)pentanoate (2g): Colorless oil. IR (KBr): ν = 3447, 2979, 2938, 2877, 1760, 1732, 1652, 1598, 1494, 1467, 1448, 1374, 1293, 1267, 1211, 1192, 1179, 1093, 1077, 1022, 1001, 953, 875, 816, 755, 705, 670, 534 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.08$ (d, $J =$ 6.8 Hz, 6H), 1.20 (t, $J = 7.2$ Hz, 3H), 2.45 (s, 3H), 3.01–3.11 (m, 1H), 4.13 (q, $J = 7.2$ Hz, 2H), 5.35 (s, 1H), 7.36 (d, $J =$ 7.2 Hz, 2H), 7.83 (d, $J = 7.2$ Hz, 2H); ^{13}C NMR (100 MHz): $\delta = 13.82$, 17.60, 17.87, 21.69, 37.32, 62.63, 79.03, 128.25, 129.92, 132.33, 145.75, 163.83, 202.91; HRMS (ESI): $m/z =$ 351.0868, calcd. for $C_{15}H_{20}O_6SNa$ $[M+Na]^+$: 351.0873.

Ethyl 4,4-dimethyl-3-oxo-2-(tosyloxy)pentanoate (2h): White solid, mp 42–43 °C. IR (KBr): ν = 3430, 2977, 2938, 2910, 2875, 1926, 1756, 1725, 1596, 1476, 1400, 1367, 1335, 1294, 1252, 1216, 1188, 1176, 1095, 1069, 1039, 10247, 994, 935, 907, 873, 832, 814, 752, 707, 697, 659, 630, 591, 5587, 547 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.18$ (t, $J =$ 7.6 Hz, 3H), 1.19 (s, 9H), 2.43 (s, 3H), 4.08–4.15 (m, 2H), 5.70 (s, 1H), 7.33 (d, $J = 8.0$ Hz, 2H), 7.82 (d, $J = 8.0$ Hz, 2H); ^{13}C NMR (100 MHz): $\delta = 13.74$, 21.62, 26.09, 44.94, 62.46, 75.22, 128.21, 129.75, 132.68, 145.56, 164.33, 203.05; HR-MS (ESI): $m/z = 365.1024$, calcd. for $C_{16}H_{22}O_6SNa$ $[M+Na]^+$: 365.1029.

Ethyl 3-oxo-2-(tosyloxy)butanoate (2i):[3] Colorless oil. ^1H NMR (400 MHz, $CDCl_3$, keto-enol): $\delta = 1.07$ (t, $J =$ 7.2 Hz, 0.62H), 1.19 (t, $J = 7.2$ Hz, 3H), 1.98 (s, 0.6H), 2.27 (s, 3H), 2.44 (s, 3H), 4.00 (q, $J = 7.2$ Hz, 0.39H), 4.13 (q, $J =$ 7.2 Hz, 2H), 5.17 (s, 1H), 7.35 (d, $J = 7.6$ Hz, 2H), 7.81 (d, $J = 7.6$ Hz, 2H), 11.54 (s, 0.18H); ^{13}C NMR (100 MHz): $\delta =$ 13.61, 13.68, 14.04, 17.32, 21.51, 21.56, 26.46, 29.53, 61.22, 62.66, 80.45, 118.09, 128.09, 128.34, 129.56, 129.91, 132.04, 133.09, 145.27, 145.80, 163.30, 170.84, 196.93.

1,3-Dioxo-1,3-diphenylpropan-2-yl 4-methylbenzenesulfonate (2j):[5] White solid, mp 89 °C. ^1H NMR (400 MHz, $CDCl_3$, keto-enol): $\delta = 2.21$ (s, 3H), 2.31 (s, 1H), 6.59 (s, 0.34H), 6.79 (d, $J = 8.0$ Hz, 2H), 7.12 (d, $J = 8.0$ Hz, 0.71H), 7.17 (d, $J = 8.0$ Hz, 2H), 7.27–7.40 (m, 7H), 7.49 (t, $J =$ 7.2 Hz, 0.85H), 7.61 (d, $J = 8.0$ Hz, 0.71H), 7.70 (d, $J =$ 7.2 Hz, 4H), 7.87 (d, $J = 7.2$ Hz, 1.5H), 15.55 (s, 1H); ^{13}C NMR (100 MHz): $\delta = 21.50$, 83.82, 126.93, 128.02, 128.20, 128.40, 128.65, 129.16, 129.28, 129.64, 129.76, 130.61, 130.79, 131.94, 132.36, 133.58, 134.05, 134.31, 145.05, 145.57, 183.39, 189.88.

1,3-Dioxo-1-phenylbutan-2-yl 4-methylbenzenesulfonate (2k):[29] White solid, mp 89–90 °C. ^1H NMR (400 MHz, $CDCl_3$, keto-enol): $\delta = 2.28$ (s, 0.51H), 2.32 (s, 3H), 2.39 (s, 3H), 2.42 (s, 0.51H), 5.96 (s, 0.15H), 6.95 (d, $J = 8.0$ Hz, 2H), 7.20 (t, $J = 7.6$ Hz, 2H), 7.34 (d, $J = 8.0$ Hz, 3H) 7.42 (d, $J = 7.6$ Hz, 2H), 7.59 (t, $J = 7.6$ Hz, 0.23H), 7.74 (d, $J =$ 8.0 Hz, 0.29H), 7.83 (d, $J = 7.6$ Hz, 0.30H), 15.18 (s, 1H); ^{13}C NMR (100 MHz): $\delta = 21.55$, 22.60, 26.56, 29.66, 84.57, 127.71, 127.76, 127.97, 128.16, 128.44, 128.65, 128.69, 129.41, 129.44, 129.96, 130.94, 131.42, 133.28, 134.40, 145.28, 179.72, 191.51.

2,4-Dioxopentan-3-yl 4-methylbenzenesulfonate (2l):[5] White solid, mp 82 °C. ^1H NMR (400 MHz, $CDCl_3$, enol form): $\delta = 1.95$ (s, 6H), 2.48 (s, 3H), 7.39 (d, $J = 7.6$ Hz, 2H), 7.82 (d, $J = 7.6$ Hz, 2H), 14.76 (s, 1H); ^{13}C NMR (100 MHz): $\delta = 21.31$, 21.73, 128.50, 130.16, 132.29, 146.04, 187.33.

1-(Dimethylamino)-1,3-dioxobutan-2-yl 4-methylbenzenesulfonate (2m): White solid, mp: 80–82 °C. IR (KBr): ν = 3454, 3085, 3051, 3029, 2945, 1952, 1838, 1735, 1651, 1595, 1496, 1455, 1417, 1401, 1384, 1365, 1301, 1255, 1190, 1172, 1122, 1093, 1042, 1015, 969, 880, 817, 797, 733, 708, 697, 684, 665, 633, 600, 569, 482 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 2.24$ (s, 3H), 2.45 (s, 3H), 2.85 (s, 3H), 3.00 (s, 3H), 5.53 (s, 1H), 7.36 (d, $J = 8.0$ Hz, 2H) 7.83 (d, $J = 8.0$ Hz, 2H); ^{13}C NMR (100 MHz): $\delta = 21.71$, 26.54, 36.15, 37.28, 79.83, 128.18, 129.93, 132.42, 145.79, 162.87, 199.88; HR-MS (ESI): $m/z = 322.0723$, calcd. for $C_{13}H_{17}NO_5SNa$ $[M+Na]^+$: 322.0719.

Ethyl 2-(methylsulfonyloxy)-3-oxo-3-phenylpropanoate (2n):[7] Light yellow oil. ^1H NMR (400 MHz, $CDCl_3$): $\delta =$ 1.24 (t, $J = 7.2$ Hz, 3H), 3.27 (s, 3H), 4.29 (q, $J = 7.2$ Hz, 2H), 6.22 (s, 1H), 7.52 (t, $J = 7.6$ Hz, 2H), 7.66 (t, $J = 7.6$ Hz, 1H), 8.03 (d, $J = 7.6$ Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 13.82$, 39.65, 63.04, 77.44, 128.93, 129.37, 133.42, 134.65, 164.55, 187.99.

Typical Procedure for α-Acetoxylation of β-Dicarbonyl Compounds

To a solution of ethyl benzoylacetate (**1a**) (192 mg, 1 mmol) in 5 mL of dichloromethane in a 10-mL round-bottom flask was added acetic acid (3 mL) and *p*-iodotoluene difluoride (384 mg, 1.5 mmol). The reaction mixture was stirred at room temperature and monitored by TLC. After 50 min, the resulting mixture was diluted with dichloromethane (50 mL). Then, the mixture was washed with saturated aqueous $NaHCO_3$ (30 mL) and saturated aqueous $Na_2S_2O_3$ (5 mL). The separated aqueous phase was extracted with dichloromethane (50 mL). The combined organic layer was washed with brine, dried over anhydrous Na_2SO_4 and concentrated under vacuum to afford the crude product which was purified by flash column chromatograpy (PE-EtOAc, 9:1) to give **3a** as a colorless oil; yield: 235 mg (94%).[9d] ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.22$ (t, $J = 7.2$ Hz, 3H), 2.23 (s, 3H), 4.25 (q, $J = 7.2$ Hz, 2H), 6.33 (s, 1H), 7.50 (t, $J = 7.2$ Hz, 2H), 7.63 (t, $J = 7.2$ Hz, 1H), 8.01 (d, $J = 7.2$ Hz, 2H); ^{13}C NMR (100 MHz): $\delta = 13.88$, 20.51, 62.51, 74.47, 128.47, 128.77, 129.20, 134.19, 134.21, 165.15, 169.55, 189.66.

Ethyl 2-acetoxy-3-(4-methoxyphenyl)-3-oxopropanoate (3b): Colorless oil. IR (KBr): ν = 2983, 2940, 2910, 2844, 1751, 1686, 1601, 1575, 1513, 1464, 1445, 1423, 1374, 1311, 1264, 1229, 1208, 1174, 1094, 1026, 953, 923, 842, 813, 657 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.23$ (t, $J =$ 7.2 Hz, 3H), 2.23 (s, 3H), 3.89 (s, 3H), 4.25 (q, $J = 7.2$ Hz, 2H), 6.29 (s, 1H), 6.97 (d, $J = 8.8$ Hz, 2H), 8.01 (d, $J =$ 8.8 Hz, 2H); ^{13}C NMR (100 MHz): $\delta = 13.90$, 20.52, 55.55, 62.38, 74.37, 114.00, 127.05, 131.70, 164.40, 165.39, 169.58, 187.86; HR-MS (ESI): $m/z = 303.0846$, calcd. for $C_{14}H_{16}O_6Na$ $[M+Na]^+$: 303.0839.

Ethyl 2-acetoxy-3-(4-chlorophenyl)-3-oxopropanoate (3c): Colorless oil. IR (KBr): ν = 3095, 2984, 2940, 1754, 1698, 1590, 1572, 1402, 1374, 1225, 1205, 1093, 1024, 1013, 943, 921, 838, 788, 771 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ = 1.16 (t, *J* = 7.2 Hz, 3H), 2.16 (s, 3H), 4.18 (q, *J* = 7.2 Hz, 2H), 6.19 (s, 1H), 7.41 (d, *J* = 8.4 Hz, 2H), 7.88 (d, *J* = 8.4 Hz, 2H); ^{13}C NMR (100 MHz): δ = 13.89, 20.47, 62.64, 74.55 129.15, 130.59, 132.47, 140.84, 164.88, 169.44, 188.55; HR-MS (ESI): *m/z* = 285.0524, calcd. for $C_{13}H_{14}O_5$ $[M+H]^+$: 285.0524.

Ethyl 2-acetoxy-3-oxo-3-p-tolylpropanoate (3d): Colorless oil. IR (KBr): ν = 3447, 2984, 2940, 1751, 1694, 1607, 1446, 1410, 1374, 1229, 1210, 1185, 1094, 1025, 942, 922, 887, 850, 825, 728, 657, 606, 565 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ = 1.15 (t, *J* = 7.2 Hz, 3H), 2.15 (s, 3H), 2.36 (s, 3H), 4.17 (q, *J* = 7.2 Hz, 2H), 6.24 (s, 1H), 7.22 (d, *J* = 8.0 Hz, 2H), 7.83 (d, *J* = 8.0 Hz, 2H); ^{13}C NMR (100 MHz): δ = 13.89, 20.52, 21.77, 62.42, 74.41, 129.34, 129.47, 131.65, 145.37, 165.28, 169.55, 189.14; HR-MS (ESI): *m/z* = 287.0898, calcd. for $C_{14}H_{16}O_5Na$ $[M+Na]^+$: 287.0890.

Ethyl 2-acetoxy-3-(naphthalen-2-yl)-3-oxopropanoate (3e): Colorless oil. IR (KBr): ν = 3060, 2984, 2939, 1751, 1692, 1627, 1597, 1468, 1373, 1220, 1126, 1094, 1023, 961, 933, 866, 821, 753 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ = 1.11 (t, *J* = 7.2 Hz, 3H), 2.15 (s, 3H), 4.16 (q, *J* = 7.2 Hz, 2H), 6.41 (s, 1H), 7.48 (t, *J* = 7.2 Hz, 1H), 7.54 (t, *J* = 7.2 Hz, 1H), 7.78 (d, *J* = 8.0 Hz, 1H), 7.82 (d, *J* = 8.8 Hz, 1H), 7.90 (d, *J* = 8.0 Hz, 1H), 7.94 (d, *J* = 8.8 Hz, 1H), 8.48 (s, 1H); ^{13}C NMR (100 MHz): δ = 13.82, 20.45, 62.43, 74.42, 124.07, 126.99, 127.73, 128.64, 129.14, 129.79, 131.43, 131.50, 132.21, 135.90, 165.16, 169.54, 189.47; HR-MS (ESI): *m/z* = 323.0886, calcd. for $C_{17}H_{16}O_5Na$ $[M+Na]^+$: 323.0890.

Ethyl 2-acetoxy-3-(furan-2-yl)-3-oxopropanoate (3f): Colorless oil. IR (KBr): ν = 3467, 3137, 2986, 2942, 2910, 1755, 1684, 1568, 1465, 1395, 1374, 1215, 1164, 1084, 1023, 954, 906, 884, 863, 774, 593, 509 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ = 1.24 (t, *J* = 7.2 Hz, 3H), 2.25 (s, 3H), 4.26 (q, *J* = 7.2 Hz, 2H), 6.17 (s, 1H), 6.62 (dd, *J* = 1.6 Hz, 3.6 Hz, 1H), 7.42 (d, *J* = 3.6 Hz, 1H), 7.69 (s, 1H); ^{13}C NMR (100 MHz): δ = 13.90, 20.45, 62.54, 74.06, 112.83, 120.50, 147.93, 150.20, 164.75, 169.43, 177.72; HR-MS (ESI): *m/z* = 263.0532, calcd. for $C_{11}H_{12}O_6Na$ $[M+Na]^+$: 263.0526.

Ethyl 2-acetoxy-4-methyl-3-oxopentanoate (3g):[30] Colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ = 1.12 (d, *J* = 6.8 Hz, 3H), 1.17 (d, *J* = 6.8 Hz, 3H), 1.30 (t, *J* = 7.2 Hz, 3H), 2.22 (s, 3H), 3.00–3.07 (m, 1H), 4.28 (q, *J* = 7.2 Hz, 2H), 5.65 (s, 1H); ^{13}C NMR (100 MHz): δ = 13.98, 17.67, 18.37, 20.44, 38.11, 62.42, 76.12, 164.82, 169.47, 203.74.

Ethyl 2-acetoxy-4,4-dimethyl-3-oxopentanoate (3h): Colorless oil. IR (KBr): ν = 3649, 3430, 2977, 2940, 2911, 2876, 1757, 1722, 1480, 1372, 1341, 1205, 1088, 1048, 1021, 944, 854, 727, 656, 600, 568 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ = 1.21 (s, 9H), 1.26 (t, *J* = 7.2 Hz, 3H), 2.17 (s, 3H), 4.22 (q, *J* = 7.2 Hz, 2H), 5.89 (s, 1H); ^{13}C NMR (100 MHz): δ = 13.88, 20.34, 26.10, 44.60, 62.20, 72.09, 165.32, 169.40, 204.99; HR-MS (ESI): *m/z* = 253.1054, calcd. for $C_{11}H_{18}O_5Na$ $[M+Na]^+$: 253.1046.

Ethyl 2-acetoxy-3-oxobutanoate (3i):[1e] Colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ = 1.28 (t, *J* = 7.2 Hz, 3H), 2.20 (s, 3H), 2.31 (s, 3H), 4.25 (q, *J* = 7.2 Hz, 2H), 5.46 (s, 1H); ^{13}C NMR (100 MHz): δ = 13.90, 20.30, 27.10, 62.41, 76.68, 164.39, 169.38, 197.46.

1,3-Dioxo-1,3-diphenylpropan-2-yl acetate (3j):[9b] White solid, mp 94–95 °C. ^1H NMR (400 MHz, $CDCl_3$): δ = 2.24 (s, 3H), 7.00 (s, 1H), 7.47 (t, *J* = 7.6 Hz, 4H), 7.60 (t, *J* = 7.6 Hz, 2H), 8.04 (d, *J* = 7.6 Hz, 4H); ^{13}C NMR (100 MHz): δ = 20.64, 79.99, 128.76, 129.41, 134.20, 134.28, 169.33, 191.04.

1,3-Dioxo-1-phenylbutan-2-yl acetate (3k):[31] Colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ = 2.24 (s, 3H), 2.30 (s, 3H), 6.26 (s, 1H), 7.49 (t, *J* = 7.2 Hz, 2H), 7.62 (t, *J* = 7.2 Hz, 1H), 8.00 (d, *J* = 7.2 Hz, 2H); ^{13}C NMR (100 MHz): δ = 20.54, 26.85, 82.22, 128.34, 128.75, 129.47, 134.30, 169.30, 190.84, 199.45.

1-(Dimethylamino)-1,3-dioxobutan-2-yl acetate (3m): Colorless oil. IR (KBr): ν = 3481, 2940, 1739, 1653, 1501, 1405, 1373, 1231, 1148, 1073, 1009, 987, 920, 860, 824, 717, 671, 605, 558, 533, 486 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ = 2.22 (s, 3H), 2.29 (s, 3H), 2.98 (s, 3H), 3.12 (s, 3H), 5.72 (s, 1H); ^{13}C NMR (100 MHz): δ = 20.52, 26.73, 36.16, 37.33, 77.21, 164.26, 169.51, 200.66; HR-MS (ESI): *m/z* = 210.0745, calcd. for $C_8H_{13}NO_4Na$ $[M+Na]^+$: 210.0737.

Typical Procedure for α-Phosphoryloxylation of β-Dicarbonyl Compounds

To a solution of ethyl benzoylacetate (**1a**) (192, 1 mmol) in 5 mL of dichloromethane in a 10-mL round-bottom flask were added diphenyl phosphate (750 mg, 3.0 mmol) and *p*-iodotoluene difluoride (384 mg, 1.5 mmol). The reaction mixture was stirred at room temperature and monitored by TLC. After 15 min, the resulting mixture was diluted with dichloromethane (50 mL). Then, the mixture was washed with saturated aqueous $NaHCO_3$ (5 mL) and saturated aqueous $Na_2S_2O_3$ (5 mL). The separated aqueous phase was extracted with dichloromethane (20 mL). The combined organic layer was washed with brine, dried over anhydrous Na_2SO_4 and concentrated under vacuum to afford the crude product which was purified by flash column chromatograpy (PE-EtOAc, 4:1) to give **4a** as a light red oil; yield: 378 mg (86%). IR (KBr): ν = 3373, 3071, 3046, 2986, 2938, 1699, 1596, 1499, 1473, 1451, 1375, 1317, 1217, 1167, 1112, 1071, 1025, 1000, 982, 830, 755, 690, 509 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ = 1.16 (t, *J* = 7.2 Hz, 3H), 4.22 (q, *J* = 7.2 Hz, 2H), 6.11 (d, *J* = 9.2 Hz, 1H), 7.11–7.14 (m, 3H), 7.19–7.26 (m, 3H), 7.29–7.37 (m, 4H), 7.42 (t, *J* = 7.6 Hz, 2H), 7.58 (t, *J* = 7.6 Hz, 1H), 7.95 (d, *J* = 7.6 Hz, 2H); ^{13}C NMR (100 MHz): δ = 13.79, 62.75, 77.85 (d, *J* = 5.5 Hz), 120.09 (d, *J* = 4.8 Hz), 120.20 (d, *J* = 4.8 Hz), 125.61, 128.69, 129.38, 129.71 (d, *J* = 3.7 Hz), 133.48, 134.23, 149.94 (d, *J* = 7.5 Hz), 150.28 (d, *J* = 7.5 Hz), 164.86 (d, *J* = 5.7 Hz), 188.82 (d, *J* = 6.9 Hz); ^{31}P NMR (121 MHz, $CDCl_3$): δ = −12.80; HR-MS (ESI): *m/z* = 441.1097, calcd. for $C_{23}H_{22}NO_7P$ $[M+H]^+$: 441.1098.

1,3-Dioxo-1,3-diphenylpropan-2-yl diphenyl phosphate (4j):[10] White solid, mp 102–104 °C. ^1H NMR (400 MHz, $CDCl_3$): δ = 6.86 (d, *J* = 8.8 Hz, 1H), 7.15–7.19 (m, 6H), 7.25–7.28 (m, 4H), 7.38 (t, *J* = 7.2 Hz, 4H), 7.53 (t, *J* = 7.2 Hz, 2H), 8.00 (d, *J* = 7.2 Hz, 4H); ^{13}C NMR (100 MHz): δ = 84.01 (d, *J* = 6.7 Hz), 115.28, 120.15 (d, *J* = 4.8 Hz), 125.65, 128.70, 129.65, 129.75, 133.61, 134.29, 150.08 (d, *J* = 7.4 Hz), 190.26 (d, *J* = 5.3 Hz); ^{31}P NMR (121 MHz, $CDCl_3$): δ = −13.10.

1-(Dimethylamino)-1,3-dioxobutan-2-yl diphenyl phosphate (4m): Light red oil. IR (KBr): ν = 3354, 2947, 1728, 1645, 1606, 1595, 1500, 1473, 1408, 1361, 1229, 1167, 1089,

1024, 960, 888, 830, 813, 757, 693, 658, 618, 529, 510 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 2.15$ (s, 3H), 2.85 (s, 3H), 2.93 (s, 3H), 5.57 (d, $J = 8.4$ Hz, 1H), 7.13–7.21 (m, 6H), 7.27–7.31 (m, 4H); ^{13}C NMR (100 MHz): $\delta = 26.20$, 36.25, 37.30, 79.89 (d, $J = 5.9$ Hz), 120.10 (d, $J = 4.9$ Hz), 120.29 (d, $J = 4.7$ Hz), 125.76, 129.81, 129.90, 150.21 (d, $J = 6.9$ Hz), 163.61 (d, $J = 4.8$ Hz), 200.74 (d, $J = 7.0$ Hz); ^{31}P NMR (121 MHz, $CDCl_3$): $\delta = -12.80$; HR-MS (MALDI): $m/z =$ 400.0924, calcd. for $C_{18}H_{20}NO_6PNa$ $[M+Na]^+$: 400.0921.

Typical Procedure for α-Methoxylation of β-Dicarbonyl Compounds

To a solution of ethyl benzoylacetate (**1a**) (192 mg, 1 mmol) in 5 mL of methanol in a 10-mL round-bottom flask was added *p*-iodotoluene difluoride (384 mg, 1.5 mmol). The reaction mixture was stirred at room temperature and monitored by TLC. After 4 h, the resulting mixture was diluted with dichloromethane (50 mL). Then, the mixture was washed with saturated aqueous $NaHCO_3$ (5 mL) and saturated aqueous $Na_2S_2O_3$ (5 mL). The separated aqueous phase was extracted with dichloromethane (20 mL). The combined organic layer was washed with brine, dried over anhydrous Na_2SO_4 and concentrated under vacuum to afford the crude product which was purified by flash column chromatograpy (PE-EtOAc, 9:1) to give **5a** as a colorless oil; yield: 184 mg (83%). IR (KBr): $\nu = 3629$, 3546, 3464, 2985, 2941, 2909, 2878, 2085, 1890, 1741, 1466, 1448, 1374, 1301, 1240, 1098, 1047, 938, 918, 847, 786, 635, 608 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.20$ (t, $J = 7.2$ Hz, 3H), 3.54 (s, 3H), 4.25 (q, $J = 7.2$ Hz, 2H), 4.94 (s, 1H), 7.48 (t, $J = 7.2$ Hz, 2H), 7.61 (t, $J = 7.2$ Hz, 1H), 8.07 (d, $J = 7.2$ Hz, 2H); ^{13}C NMR (100 MHz): $\delta = 13.90$, 58.59, 61.91, 85.02, 128.58, 129.31, 130.09, 133.92, 167.44, 192.46; HR-MS (ESI): $m/z = 245.0786$, calcd. for $C_{12}H_{14}O_4$ Na $[M+Na]^+$: 245.0784.

Ethyl 2-methoxy-3-(4-methoxyphenyl)-3-oxopropanoate (5b): Colorless oil. IR (KBr): $\nu = 3630$, 3552, 3464, 2984, 2941, 2908, 2878, 1741, 1601, 1448, 1374, 1301, 1241, 1173, 1098, 1048, 938, 847, 787, 634, 608 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.21$ (t, $J = 7.2$ Hz, 3H), 3.52 (s, 3H), 3.88 (s, 3H), 4.24 (q, $J = 7.2$ Hz, 2H), 4.88 (s, 1H), 6.94 (d, $J = 9.2$ Hz, 2H), 8.08 (d, $J = 9.2$ Hz, 2H); ^{13}C NMR (100 MHz): $\delta = 13.98$, 55.48, 58.46, 61.85, 85.27, 113.85, 127.04, 131.86, 164.18, 167.70, 190.90; HR-MS (ESI): $m/z = 253.1075$, calcd. for $C_{13}H_{17}O_5$ $[M+H]^+$: 253.1070.

Ethyl 3-(4-chlorophenyl)-2-methoxy-3-oxopropanoate (5c): Colorless oil. IR (KBr): $\nu = 3629$, 3546, 3464, 2985, 2942, 2909, 1739, 1479, 1465, 1448, 1374, 1241, 1097, 1047, 938, 918, 848, 787, 635, 608 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.21$ (t, $J = 7.2$ Hz, 3H), 3.53 (s, 3H), 4.25 (q, $J = 7.2$ Hz, 2H), 4.86 (s, 1H), 7.45 (d, $J = 8.8$ Hz, 2H), 8.03 (d, $J = 8.8$ Hz, 2H); ^{13}C NMR (100 MHz): $\delta = 13.96$, 58.68, 62.06, 85.38, 128.97, 130.85, 132.27, 140.53, 167.26, 191.39; HR-MS (ESI): $m/z = 257.0577$, calcd. for $C_{12}H_{14}O_4$ $[M+H]^+$: 257.0575.

Ethyl 2-methoxy-3-oxo-3-p-tolylpropanoate (5d): Colorless oil. IR (KBr): $\nu = 3465$, 2985, 2941, 2909, 1742, 1466, 1448, 1374, 1242, 1098, 1047, 938, 847, 787, 635, 608 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.21$ (t, $J = 7.2$ Hz, 3H), 2.41 (s, 3H), 3.52 (s, 2H), 4.24 (q, $J = 7.2$ Hz, 2H), 4.91 (s, 1H), 7.27 (d, $J = 8.4$ Hz, 2H), 7.97 (d, $J = 8.4$ Hz, 2H); ^{13}C NMR (100 MHz): $\delta = 13.96$, 21.72, 58.53, 61.87, 85.11, 129.32, 129.47, 131.58, 145.01, 167.56, 192.06; HR-MS (ESI): $m/z = 259.0947$, calcd. for $C_{13}H_{16}O_4Na$ $[M+Na]^+$: 259.0941.

Ethyl 2-methoxy-3-(naphthalen-2-yl)-3-oxopropanoate (5e): Colorless oil. IR (KBr): $\nu = 3629$, 3546, 3464, 2984, 2941, 2909, 2878, 1751, 1465, 1447, 1374, 1300, 1241, 1098, 1241, 1098, 1048, 938, 918, 847, 786, 635, 608 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.19$ (t, $J = 7.2$ Hz, 3H), 3.58 (s, 3H), 4.21–4.29 (m, 2H), 5.05 (s, 1H), 7.55–7.65 (m, 2H), 7.89 (t, $J = 9.2$ Hz, 2H), 8.00 (d, $J = 8.0$ Hz, 1H), 8.08 (d, $J = 8.0$ Hz, 1H), 8.69 (s, 1H); ^{13}C NMR (100 MHz): $\delta = 13.98$, 58.65, 61.99, 85.36, 124.37, 126.85, 127.75, 128.51, 129.01, 130.00, 131.37, 131.81, 132.37, 135.94, 167.56, 192.47; HR-MS (ESI): $m/z = 295.0945$, calcd. for $C_{16}H_{16}O_4Na$ $[M+Na]^+$: 295.0941.

Ethyl 3-(furan-2-yl)-2-methoxy-3-oxopropanoate (5f): Colorless oil. IR (KBr): $\nu = 3628$, 3550, 3464, 2985, 2942, 2909, 2086, 1889, 1739, 1568, 1479, 1466, 1447, 1374, 1241, 1098, 1047, 938, 918, 847, 786, 810, 635, 608 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.24$ (t, $J = 7.2$ Hz, 3H), 3.55 (s, 3H), 4.25 (q, $J = 7.2$ Hz, 2H), 4.82 (s, 1H), 6.59–6.60 (m, 1H), 7.50 (d, $J = 3.6$ Hz, 1H), 7.70 (s, 1H); ^{13}C NMR (100 MHz): $\delta = 13.77$, 58.53, 61.75, 84.03, 112.39, 120.71, 147.59, 149.86, 166.68, 180.61; HR-MS (ESI): $m/z = 235.0577$, calcd. for $C_{10}H_{12}O_5Na$ $[M+Na]^+$: 235.0577.

Methyl 2-methoxy-1-oxo-2,3-dihydro-1*H*-indene-2-carboxylate (5n): Colorless oil. IR (KBr): $\nu = 3629$, 3566, 3464, 2985, 2942, 2909, 2878, 1740, 1466, 1447, 1373, 1301, 1240, 1098, 1240, 1098, 1047, 938, 917, 847, 787, 635, 608 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 3.32$ (d, $J = 17.2$ Hz, 1H), 3.53 (s, 3H), 3.67 (d, $J = 17.2$ Hz, 1H), 3.77 (s, 3H), 7.43 (t, $J = 7.6$ Hz, 1H), 7.49, (d, $J = 7.6$ Hz, 1H), 7.67 (t, $J = 7.6$ Hz, 1H), 7.81 (d, $J = 7.6$ Hz, 1H); ^{13}C NMR (100 MHz): $\delta =$ 37.67, 52.48, 53.97, 85.35, 124.79, 126.28, 127.91, 133.89, 135.83, 151.40, 169.70, 198.19; HR-MS (ESI): $m/z =$ 243.0632, calcd. for $C_{12}H_{12}O_4Na$ $[M+Na]^+$: 243.0628.

Ethyl 2-methoxy-3-oxo-3-(pyridin-2-yl)propanoate (5o): Colorless oil. IR (KBr): $\nu = 3629$, 3546, 3464, 2985, 2941, 2909, 2256, 2087, 1739, 1479, 1466, 1447, 1300, 1243, 1098, 1047, 938, 918, 847, 787, 736, 704, 644, 608 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.17$ (t, $J = 7.2$ Hz, 3H), 3.61 (s, 3H), 4.21 (q, $J = 7.2$ Hz, 2H), 5.57 (s, 1H), 7.49–7.52 (m, 1H), 7.86–7.90 (m, 1H), 8.08 (d, $J = 7.2$ Hz, 1H), 8.68 (d, $J =$ 4.4 Hz, 1H); ^{13}C NMR (100 MHz): $\delta = 13.84$, 59.21, 61.50, 81.91, 122.63, 127.61, 137.05, 148.88, 151.56, 167.32, 193.11; HR-MS (ESI): $m/z = 224.0921$, calcd. for $C_{11}H_{14}NO_4$ $[M+H]^+$: 224.0917.

Ethyl 2-dimethoxy-3-oxo-3-(pyridin-2-yl)propanoate: Colorless oil. IR (KBr): $\nu = 3056$, 2964, 2941, 2838, 1765, 1720, 1583, 1466, 1439, 1391, 1369, 1305, 1286, 1260, 1242, 1203, 1141, 1097, 1064, 1032, 997, 888, 906, 857, 838, 757, 742, 779, 687, 633, 619 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.29$ (t, $J = 7.2$ Hz, 3H), 3.32 (s, 6H), 4.23 (q, $J = 7.2$ Hz, 2H), 7.43–7.47 (m, 1H), 7.82–7.86 (dt, $J = 1.6$ Hz, 8.0 Hz, 1H), 8.08 (d, $J = 8.0$ Hz, 1H), 8.61–8.62 (m, 1H); ^{13}C NMR (100 MHz): $\delta = 13.76$, 50.86, 61.69, 98.10, 123.28, 127.46, 136.99, 148.49, 150.51, 165.44, 190.52; HR-MS (ESI): $m/z = 254.1021$, calcd. for $C_{12}H_{16}NO_5$ $[M+H]^+$: 254.1023.

Ethyl 2-methoxy-4-methyl-3-oxopentanoate (5g): Colorless oil. IR (KBr): $\nu = 2962$, 2928, 2875, 2835, 1749, 1724, 1464, 1457, 1373, 1338, 1260, 1197, 1133, 1025, 995, 858, 803, 693 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): $\delta = 1.08$–1.11 (m, 6H), 1.29 (t, $J = 7.2$ Hz, 3H), 3.05–3.11 (m, 1H), 3.47 (s, 3H), 4.23–4.29 (m, 2H), 4.39 (s, 1H); ^{13}C NMR (100 MHz):

δ = 14.09, 17.90, 18.14, 36.98, 58.65, 61.87, 85.58, 167.24, 207.44; HR-MS (ESI): *m/z* = 211.0944, calcd. for $C_9H_{16}O_4Na$ $[M+Na]^+$: 211.0941.

Ethyl 2-methoxy-4,4-dimethyl-3-oxopentanoate (5h): Colorless oil. IR (KBr): ν = 3420, 2971, 2934, 2875, 1759, 1716, 1179, 1465, 1395, 1369, 1247, 1197, 1124, 1096, 1065, 1034, 941, 856, 822, 719, 579 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ = 1.21 (s, 9H), 1.28 (t, *J* = 7.2 Hz, 3H), 3.47 (s, 3H), 4.24 (q, *J* = 7.2 Hz, 2H), 4.64 (s, 1H); ^{13}C NMR (100 MHz): δ = 13.78, 25.90, 44.19, 58.53, 61.27, 81.74, 167.50, 206.78; HR-MS (ESI): *m/z* = 225.1105, calcd. for $C_{10}H_{18}O_4Na$ $[M+Na]^+$: 225.1097.

Ethyl 1-methoxy-2-oxocyclopentanecarboxylate (5p): Colorless oil. IR (KBr): ν = 3635, 3552, 3465, 2986, 2942, 2909, 2878, 1743, 1465, 1448, 1374, 1301, 1240, 1098, 1047, 938, 847, 787, 635, 608 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ = 1.29 (t, *J* = 7.2 Hz, 3H), 1.99–2.13 (m, 2H), 2.17–2.34 (m, 1H), 2.34–2.44 (m, 3H), 3.46 (s, 3H), 4.23–4.28 (m, 2H); ^{13}C NMR (100 MHz): δ = 14.11, 18.43, 34.63, 36.54, 54.24, 61.55, 84.57, 169.80, 210.46; HR-MS (ESI): *m/z* = 209.0787, calcd. for $C_9H_{14}O_4Na$ $[M+Na]^+$: 209.0784.

2-Methoxy-1,3-diphenylpropane-1,3-dione (5j):[32] Colorless oil. ^1H NMR (400 MHz, $CDCl_3$, keto-enol): δ = 3.24 (s, 3H), 3.55 (s, 1.6H), 5.65 (s, 0.54H), 7.42–7.56 (m, 10H), 8.09–8.14 (m, 5H), 15.80 (s, 1H); ^{13}C NMR (100 MHz): δ = 58.55, 61.44, 91.24, 128.29, 128.60, 129.11, 129.62, 130.08, 131.69, 133.98, 134.45, 134.84, 137.35, 181.90, 194.19.

2-Methoxy-1-phenyl-1,3-butanedione (5k):[33] Colorless oil. ^1H NMR (400 MHz, $CDCl_3$, keto-enol): δ = 2.25 (s, 1H), 2.32 (s, 3H), 3.42 (s, 3H), 3.47 (s, 1H), 4.97 (s, 0.3H), 7.43–7.48 (m, 4H), 8.03–8.06 (m, 3H), 14.98 (s, 1H); ^{13}C NMR (100 MHz): δ = 22.36, 26.12, 58.38, 61.29, 92.41, 128.35, 128.67, 128.75, 129.47, 130.07, 131.37, 133.68, 134.10, 136.94, 173.25, 194.76.

2-Methoxy-*N*,*N*-dimethyl-3-oxobutanamide (5m): Colorless oil. IR (KBr): ν = 3445, 2940, 2834, 2602, 2081, 1732, 1652, 1506, 1456, 1417, 1358, 1281, 1250, 1198, 1114, 1062, 1015, 978, 848, 383, 618, 562 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ = 2.24 (s, 3H), 2.96 (s, 3H), 3.03 (s, 3H), 3.42 (s, 3H), 4.52 (s, 1H); ^{13}C NMR (100 MHz): δ = 26.14, 36.10, 36.83, 58.03, 87.71, 166.09, 203.85; HR-MS (ESI): *m/z* = 182.0794, calcd. for $C_7H_{13}NO_3Na$ $[M+Na]^+$: 182.0788.

Ethyl 2-ethoxy-3-oxo-3-phenylpropanoate (5q):[11] Colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ = 1.19 (t, *J* = 7.2 Hz, 3H), 1.27 (t, *J* = 7.2 Hz, 3H), 3.60–3.68 (m, 1H), 3.70–3.78 (m, 1H), 4.23 (q, *J* = 7.2 Hz, 2H), 5.01 (s, 1H), 7.44–7.50 (m, 2H), 7.57–7.61 (m, 1H), 8.07–8.10 (m, 2H); ^{13}C NMR (100 MHz): δ = 13.96, 15.06, 61.85, 66.89, 83.72, 128.56, 129.42, 130.18, 133.85, 167.84, 192.87.

Ethyl 2-isopropoxy-3-oxo-3-phenylpropanoate (5r): Colorless oil. IR (KBr): ν = 3446, 3067, 2977, 2932, 1756, 1688, 1598, 1580, 1465, 1450, 1465, 1385, 1282, 1229, 1202, 1181, 1115, 1024, 942, 891, 841, 770, 692, 593 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$, keto-enol): δ = 1.05 (d, *J* = 6.4 Hz, 0.98H), 1.16–1.20 (m, 6H), 1.28 (d, *J* = 6.4 Hz, 3H), 1.40 (t, *J* = 7.2 Hz, 0.46H), 3.78–3.84 (m, 1H), 4.22 (q, *J* = 7.2 Hz, 2H), 4.35 (q, *J* = 7.2 Hz, 0.29H), 5.05 (s, 1H), 7.39–7.40 (m, 0.51H), 7.46 (t, *J* = 7.2 Hz, 2H), 7.58 (t, *J* = 7.2 Hz, 1H), 7.96–7.97 (m, 0.32H), 8.09 (d, *J* = 7.2 Hz, 2H), 11.76 (s, 0.14H); ^{13}C NMR (100 MHz): δ = 13.90, 21.89, 61.72, 73.22, 81.94, 127.76, 128.44, 128.86, 129.49, 130.03, 133.66, 134.17, 168.32, 193.29; HR-MS (ESI): *m/z* = 273.1102, calcd. for $C_{14}H_{18}O_4Na$ $[M+Na]^+$: 273.1097.

Supporting Information

NMR, IR and mass spectra are provided in the Supporting Information.

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