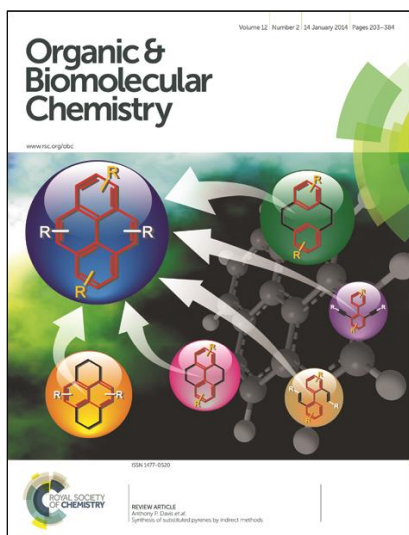




**Cross-Benzoin and Stetter-Type Reactions Mediated by
KOTBu-DMF via Electron-Transfer Process**

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Cross-Benzoin and Stetter-Type Reactions Mediated by KOtBu-DMF via Electron-Transfer Process

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The condensation of aromatic α -diketones (benzils) with aromatic aldehydes (benzoin-type reaction) and chalcones (Stetter-type reaction) in DMF in the presence of catalytic (25 mol%) KOtBu is reported. Both types of umpolung processes proceed with good efficiency and complete chemoselectivity. On the basis of spectroscopic evidences (MS analysis) of plausible intermediates and literature reports, the occurrence of different ionic pathways have been evaluated to elucidate the mechanism of a model cross-benzoin-like reaction along with a radical route initiated by an electron-transfer process to benzil from the carbamoyl anion derived from DMF. This mechanistic investigation has culminated in a different proposal, supported by calculations and a trapping experiment, based on double electron-transfer to benzil with formation of the corresponding enediolate anion as key reactive intermediate. A mechanistic comparison between the activation modes of benzils in KOtBu-DMF and KOtBu-DMSO systems is also described.

Introduction

N,N-Dimethylformamide is a common polar aprotic solvent but also an effective reagent, ligand or even catalyst employed in a number of fundamental reactions such as formylation, amidation, aminocarbonylation, cyanation, reduction, cycloaddition, dehydration, and C-H activation.¹ New roles are continuously discovered for DMF as demonstrated, for instance, by its recent use as component of novel multicomponent reactions.² Interestingly, the involvement of DMF has been also reported for a series of base-promoted radical processes like the Mizoroki-Heck-type reaction,³ the α -arylation of enolizable arylketones,⁴ and various intramolecular cyclizations.⁵ In the field of umpolung (polarity reversal) catalysis, DMF is a widely used solvent, while its active role has never been hypothesized to the best of our knowledge. The generation of acyl anion equivalents by the polarity reversal of carbonyl compounds through cyanide or *N*-heterocyclic carbene (NHC) catalysis is today a well-established methodology to access target molecules by unconventional strategies as exemplified by classical benzoin and Stetter reactions.⁶ Typically, in the majority of the above umpolung

transformations the active species is catalytically generated through electron-pair-transfer steps. Only recently the opportunities given by single electron-transfer (ET) processes have been exploited to perform the NHC-catalyzed oxidation of aldehydes with TEMPO⁷ or oxygen,⁸ the β,β -coupling of nitroalkenes,⁹ the β -hydroxylation¹⁰ and annulation of enals.¹¹ Remarkably, also the thiazolium-catalyzed benzoin condensation has been recently revisited in the light of an ET-based mechanism.¹² The formation of a radical cation of the Breslow intermediate by the suitable choice of a single-electron oxidant has been proposed for these transformations (Figure 1). Two-electron acceptors have been also utilized to oxidize the Breslow intermediate to the corresponding acylazolium ion for the production of carboxylic acids and esters.¹³

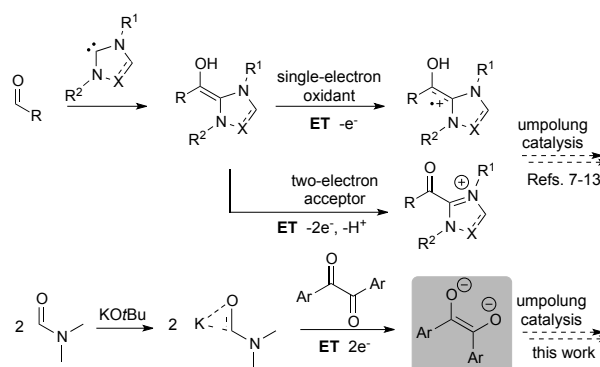


Fig 1 Umpolung reactions by electron-transfer processes: background and present work.

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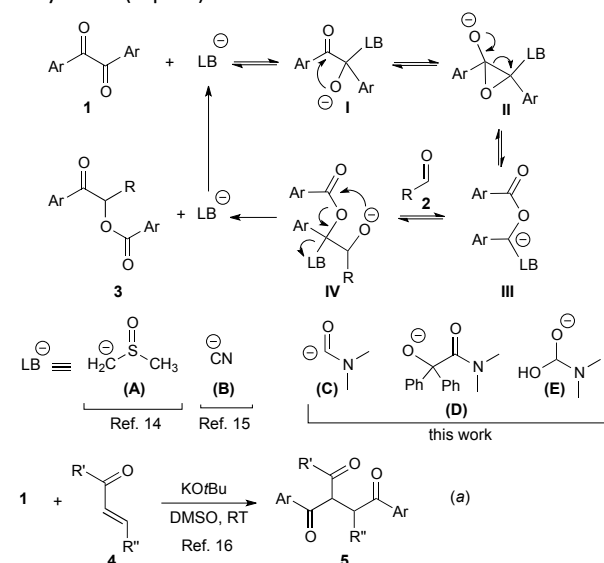
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Electronic Supplementary Information (ESI) available: [MS and EPR experiments, computational methods, NMR spectra of new compounds]. See DOI: 10.1039/x0xx00000x

Here we describe the results of our study on the chemoselective cross-benzoin and Stetter-type reactions with aromatic α -diketone donors promoted by the KOtBu-DMF system; we also report on the experimental evidences and theoretical calculations in support of a mechanism involving a two sequential ET process to the α -diketone initiated by the carbamoyl anion of DMF, which produces an enediolate anion as key reactive species of umpolung catalysis (Figure 1).

Results and Discussion

In a previous contribution we demonstrated the capability of methylsulfinyl (dimsyl) carbanion **A**, generated by deprotonation of the DMSO solvent with KOtBu, to induce the polarity reversal of diaryl α -diketones (benzils) **1** in chemoselective cross-benzoin-type reactions with aromatic aldehydes **2** leading to benzoylated benzoin **3** through a formal sequence of nucleophilic C-arylation and electrophilic O-arylation steps (Scheme 1).¹⁴ In our mechanistic interpretation, dimsyl anion **A** served as Lewis base (LB) and anion-stabilizing group to produce the reactive carbanion intermediate **III(A)** (aroyl anion equivalent) in analogy with cyanide **B** catalysis.¹⁵ The same dimsyl anion **A** proved to be effective in Stetter-like reactions of **1** with chalcones **4** affording 2-benzoyl-1,4-diones **5** as products of double C-arylation (eqn. a).¹⁶

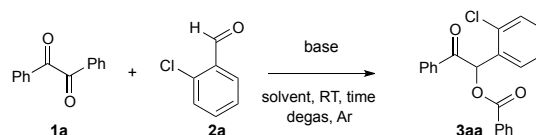


Scheme 1 General ionic pathway for the polarity reversal of benzils **1** leading to benzoylated benzoin **3**; Stetter-like reaction of **1** with chalcones **4** mediated by the dimsyl anion **A** (eqn. a).

Due to the known formation of carbamoyl anions of type **C** from N,N-disubstituted formamides with strong bases,¹⁷ the use of DMF was considered in the present study with the aim to eventually provide an improved protocol towards compounds **3** and **5** and, at the same time, better elucidate the mechanistic details of our proposal. Hence, the model reaction of benzil **1a** with *o*-chlorobenzaldehyde **2a** was performed in anhydrous DMF (argon atmosphere) in the presence of KOtBu (25 mol%); gratifyingly, the target adduct **3aa** was obtained in

almost quantitative yield after 30 minutes (Table 1, entry 1). A decrease in the amount of KOtBu (10 mol%) led to a lower yield of **3aa** (entry 2), and exposure of the reaction mixture to air significantly affected the reaction rate (entry 3). The use of equimolar KOtBu produced a complex reaction mixture where **3aa** could be detected in only trace amounts (entry 4). Other bases such as NaOtBu, NaH and DBU were also applicable furnishing, however, lower yields of **3aa** (entries 5-7). The weaker base Et₃N was completely inefficient (entry 8). Also, no product formation was observed in THF, CH₂Cl₂ and NMP, while a poor yield of **3aa** (7%) was detected in DMA (entries 9-12). To unequivocally prove the active role of DMF, the **1a/2a** coupling was performed in THF with increasing amounts of anhydrous DMF detecting a direct correlation between the yield of **3aa** and the added quantity of DMF (entries 13-14).

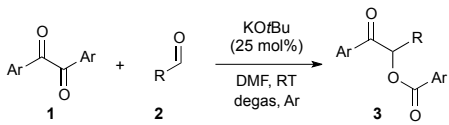
Table 1 Optimization of the model cross-benzoin-type reaction of benzil **1a** with *o*-chlorobenzaldehyde **2a**.^a



Entry	Solvent	Base (mol %)	Time (h)	Yield (%) ^b
1	DMF	KOtBu (25)	0.5	95
2	DMF	KOtBu (10)	16	50
3 ^c	DMF	KOtBu (25)	16	86
4	DMF	KOtBu (100)	1	<5
5	DMF	NaOtBu (25)	6	45
6	DMF	NaH(25)	6	38
7	DMF	DBU (25)	16	35
8	DMF	NEt ₃ (25)	60	-
9	THF	KOtBu (25)	60	-
10	CH ₂ Cl ₂	KOtBu (25)	60	-
11	NMP	KOtBu (25)	16	-
12	DMA	KOtBu (25)	16	7
13 ^d	THF	KOtBu (25)	16	5
14 ^e	THF	KOtBu (25)	16	37

^a Reaction Conditions: benzil (0.50 mmol), *o*-chloro benzaldehyde (0.50 mmol), anhydrous solvent (1.0 mL), and the stated amount of base. ^b Isolated yield. ^c Reaction conducted under open air. ^d Reaction performed in the presence of 1 equiv. of anhydrous DMF. ^e Reaction performed in the presence of 10 equiv. of anhydrous DMF.

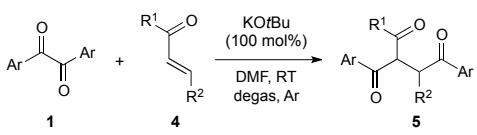
The cross-benzoin-like reaction promoted by KOtBu-DMF was applied to various α -diketones **1** and aromatic aldehydes **2** producing results similar to those previously observed in DMSO (Table 2; selected experiments are reported).¹⁴ Indeed, higher coupling efficiencies were achieved with electron-withdrawing groups installed on either α -diketone **1** or aldehyde **2**; interesting anomaly of the KOtBu-DMF system was, however, the general inertness of 4,4'-dimethylbenzil **1d** toward carbonylations with aldehydes **2** (entry 10).

Table 2 Scope of the cross-benzoin-like reactions of benzils **1** with aromatic aldehydes **2** mediated by the KOtBu-DMF system.^a


Entry ¹	Ar	R	Product	Yield (%) ^b
1	Ph (1a)	2-ClPh (2a)	3aa	95
2	Ph (1a)	2-OMe (2b)	3ab	90
3	Ph (1a)	2-MePh (2c)	3ac	47
4	Ph (1a)	3-BrPh (2d)	3ad^c	92
5	Ph (1a)	4-ClPh (2e)	3ae^c	93
6	Ph (1a)	2,3-Cl ₂ Ph (2f)	3af	80
7	Ph (1a)	Ph (2g)	3ag	51
8	2-ClPh (1b)	2-ClPh (2a)	3ba	78
9	4-CF ₃ Ph (1c)	2-BrPh (2h)	3ch	68
10	4-MePh (1d)	2-ClPh (2a)	3da	<5 ^d

^a Reaction Conditions: **1** (1.00 mmol), **2** (1.00 mmol), KOtBu (25 mol%), and anhydrous DMF (2.0 mL). ^b Isolated yield. ^c Isomeric mixture (see the ESI for details). ^d Recovered unreacted **1d** and **2a**.

Stetter-like reactions of α -diketones **1** with chalcones **4** were also examined in DMF to prepare the valuable 1,4-diones **5** (Table 3; selected examples). Couplings were optimized with an excess of **1** (2 equiv.) and equimolar KOtBu but, in general, a lower level of reaction efficiency was detected compared to DMSO-KOtBu.¹⁶ Again, the substrate **1d** proved to be completely ineffective with the DMF-based activation system (entry 8).

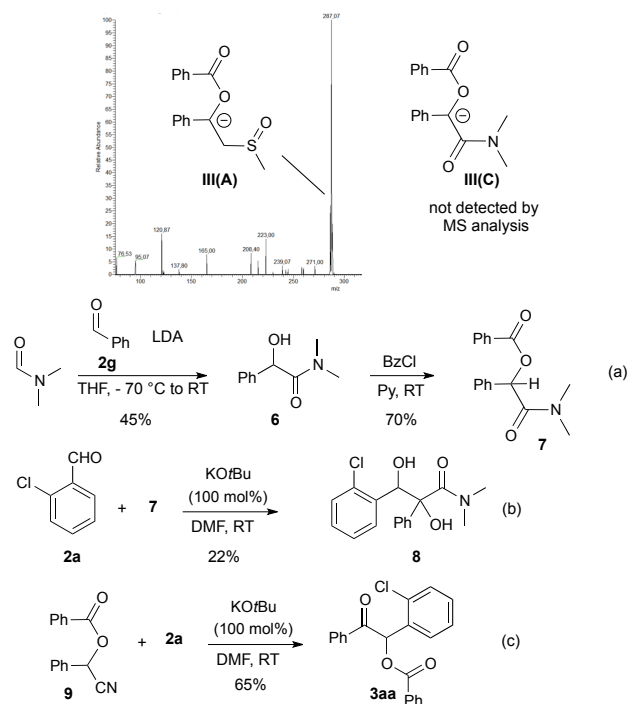
Table 3 Scope of the Stetter-like reactions of benzils **1** with chalcones **4** mediated by the KOtBu-DMF system.^a


Entry ¹	Ar	R ¹ , R ²	Product	Yield (%) ^b
1	Ph (1a)	Ph, Ph (4a)	5aa	71
2	Ph (1a)	Ph, 4-ClPh (4b)	5ab	77
3	Ph (1a)	Ph, 4-BrPh (4c)	5ac	70
4	Ph (1a)	4-ClPh, Ph (4d)	5ad^c	61
5	Ph (1a)	4-OMePh, Ph (4e)	5ae^c	42
6	Ph (1a)	4-OMePh, 4-ClPh (4f)	5af^c	41
7	4-CF ₃ Ph (1c)	Ph, Ph (4a)	5ca^c	30
8	4-MePh (1d)	Ph, 4-ClPh (4b)	5db^c	<5

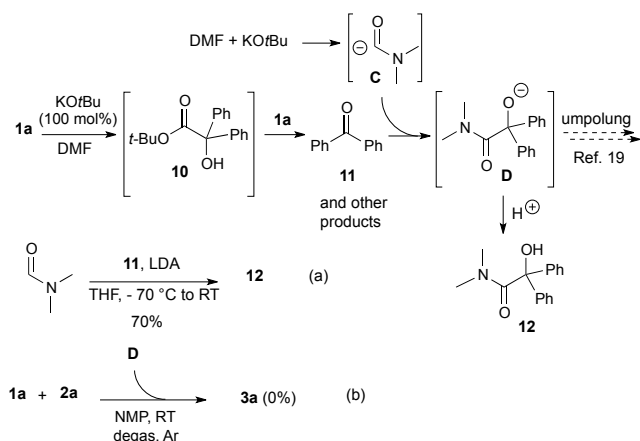
^a Reaction Conditions: **1** (1.00 mmol), **2** (0.50 mmol), KOtBu (25 mol%), and anhydrous DMF (2.0 mL). ^b Isolated yield. ^c Diastereomeric mixture.

The picture arising from the ESI-MS analyses of the model **1a/2a** coupling promoted by the KOtBu-DMF and KOtBu-DMSO systems led us to suppose a different role for the dimsilyl and carbamoyl anions **A** and **C** with possible mechanistic implications. Spectra obtained in both full-scan and MS/MS modes provided, in fact, direct evidence of the anion **III(A)**¹⁴ (m/z 287) but not of the corresponding reactive species **III(C)** (Scheme 2). Therefore, the precursor **7** of the aroyl anion

equivalent **III(C)** was suitably prepared by standard chemistry starting from benzaldehyde **2g** (eqn. *a*). When **7** was added to the DMF solution of *o*-chlorobenzaldehyde **2a** in the presence of KOtBu (1 equiv.) the only isolable product was the adduct **8** (22%; eqn. *b*), thus indicating the lack of catalyst turnover with **C** and the general inefficacy of this promoter. In a control experiment, the *O*-aroylmandelonitrile **9**,¹⁸ that is the precursor of the aroyl anion equivalent **III(B)** (Scheme 1), reacted with **2a** (equimolar KOtBu, DMF, RT) furnishing the target cross-benzoin product **3aa** in satisfactory 65% yield (Scheme 2, eqn. *c*).



At the beginning of this study, we were aware of the mechanistic proposal that Lund and co-workers suggested to explain the set of products observed in the homocoupling reaction of benzil **1a** in DMF with stoichiometric KOtBu.¹⁹ In that study it was hypothesized the crucial role for the umpolung of **1a** of the anion **D**, which is supposed to be produced after a sequence of reactions involving the initial benzylic rearrangement of **1a** to the benzylic ester **10** followed by formation of benzophenone **11** through a redox process with **1a** (Scheme 3). According to that proposal, it could be envisaged that the anion **D** could function as the active Lewis base (LB) in the **1a/2a** cross-coupling as well. To verify this hypothesis, the precursor **12** of the anion **D** was readily synthesized from benzophenone **11** (72%, eqn. *a*); then, a solution of deprotonated **12** (NaH, THF) was slowly added to the mixture of **1a** and **2a** in NMP observing, however, the complete absence of the coupling product **3aa** (eqn. *b*).



Scheme 3 Proposed mechanism (Ref. 19) for the homocoupling of benzil **1a** mediated by the KOtBu-DMF system; proof of the inability of **D** to promote the **1a/2a** coupling (eqns. a,b).

In the search for the existence of plausible intermediates of the ionic pathway depicted in Scheme 1, a real-time monitoring of the model **1a/2a** coupling was conducted by ESI-MS and NMR analyses. Both techniques confirmed a short reaction time (ca. 15 min) for this transformation; while the identification of any intermediate failed by proton and carbon NMR analysis, ESI(-)-MS spectra showed the species **E** at m/z 90 as a possible player (Scheme 1, Figure 3, and Figure S1). The Lewis base **E** could be formed by addition to DMF of the hydroxyl anion generated by deprotonation of adventitious water with KOtBu. Intriguingly, MS spectra of the **1a/2a** coupling in DMA and NMP solvents displayed a very low intensity peak of the DMA/OH adduct (m/z 121) and the absence of peak for the NMP/OH species (m/z 116),²⁰ in full agreement with the observed trend of reaction conversions in those solvents (Table 1, entries 11-12). Significantly, the peak corresponding to the isobaric species **I-III(E)** could be detected at m/z 300 (or m/z 307 for DMF- d_7) and fragmented (Figures 2-3). In principle, from the analysis of the MS/MS spectrum it would be possible to distinguish among the isobaric intermediates **I-III(E)**. The observed fragmentations were attributed to the loss of CH_2O_2 with formation of the ion at m/z 254 and to the formation of the benzoate anion at m/z 121, ascription confirmed also in the experiments carried out using DMF- d_7 (Figure S2). This latter evidence, in particular, supported the structure **III(E)**, where a release of the benzoate ion may easily take place.

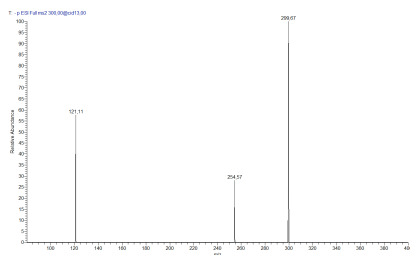


Fig. 2 MS/MS of the isobaric intermediates **I-III(E)** in DMF (m/z 300) and related signature fragments (m/z 254 and 121).

Based on these premises and literature reports on different activities of hydrated DMF,²¹ we carried out calculations to ascertain whether the anion **E** could be productively involved in the catalytic cycle of Scheme 1. The initial addition of **E** to benzil **1a** giving **I(E)** was found to be endergonic by 3.4 kcal mol⁻¹ with an energy barrier of 9.1 kcal/mol (Figure 3). Nevertheless, the rearrangement of **I(E)** to the postulated reactive intermediate **III(E)** through the epoxide **II(E)** (endergonic by 13.3 kcal mol⁻¹) was found to be an overall endergonic process (31.4 kcal mol⁻¹), thus indicating this mechanistic hypothesis very unlikely and confined to the peculiar gas phase conditions of the MS experiment.

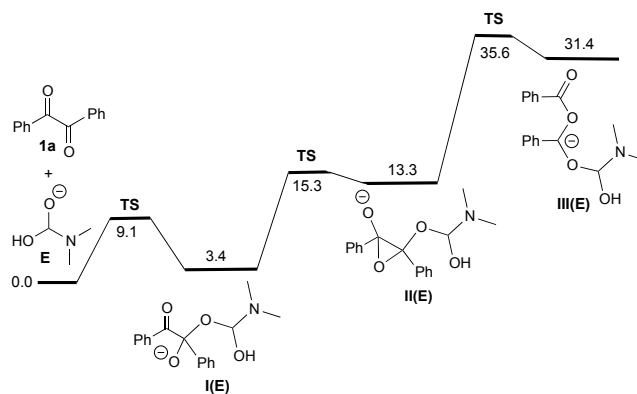
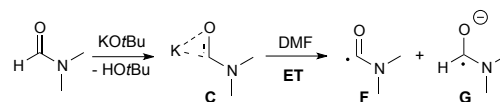


Fig. 3 Calculated ($\Delta\Delta G$ kcal mol⁻¹) energy profile of the ionic pathway of Scheme 1 with the postulated promoter **E** [M06//6-31+G(d,p) level using the PCM continuum model; see ESI for details].

As anticipated, the KOtBu-DMF system has been reported to efficiently initiate various free radical processes.³⁻⁵ The carbamoyl radical **F** is supposed to be generated by single electron-transfer from the carbamoyl anion **C** to DMF with concomitant formation of the radical anion **G** (Scheme 4).^{4,5,22}



Scheme 4. Supposed mechanism for formation of the carbamoyl radical **F**.

Indeed, in 2009 Sliwka and co-workers observed the generation of radical intermediates in basic DMF solutions via EPR analysis, although the structures of these intermediates were not identified.²³ In our study we also observed a weak uninterpretable EPR signal in the solution of KOtBu-DMF (Figure 4, solid). Intriguingly, the solution became EPR silent after the addition of benzil **1a**. Only when aldehyde **2a** was added an EPR signal emerged (Figure 4, dashed) with a g value of 2.0017 and without hyperfine structure (see below and Scheme 5 for a tentative interpretation). Moreover, its intensity reached a maximum after ca. 7 minutes (Figure S3) and then diminished, likely indicating that the radical degraded or was consumed in a subsequent reaction.

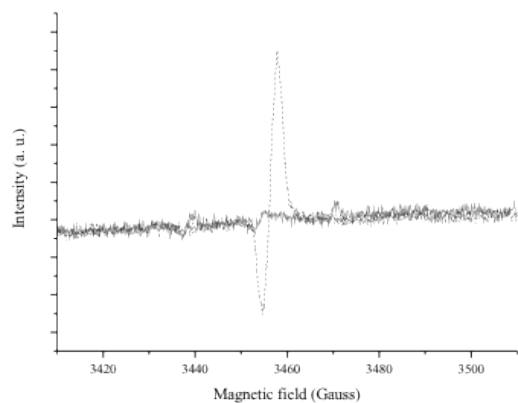


Fig. 4 EPR spectra obtained from DMF solutions containing KOtBu (0.125 M) (solid) and KOtBu (0.125 M), benzil **1a** (0.5 M), aldehyde **2a** (0.5 M) (dashed).

The same sequence of EPR experiments was repeated in the presence of the radical trap α -phenyl-*N*-*tert*-butyl nitron (PBN). While the KOtBu-DMF solution produced a weak signal of difficult interpretation (Figure 5 black line),²⁴ addition of benzil **1a** resulted in a strong and well-defined signal, which consisted of a triplet of doublets (Figure 5 red line). According to literature data²⁵ and on the basis of the obtained hyperfine splitting coupling constants ($a_N = 13.3$ gauss and $a_H = 1.77$ gauss), the EPR signal was reasonably attributed to the spin adduct of the benzil anion radical **V** with PBN (Scheme 5).²⁶

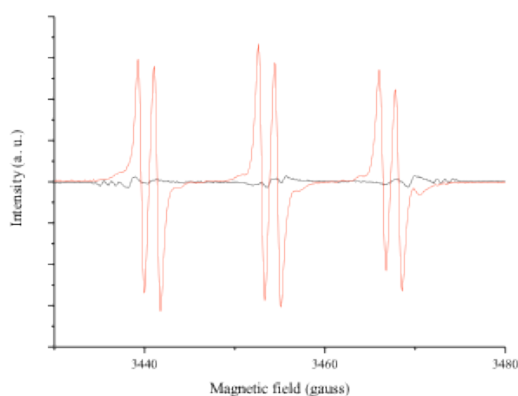
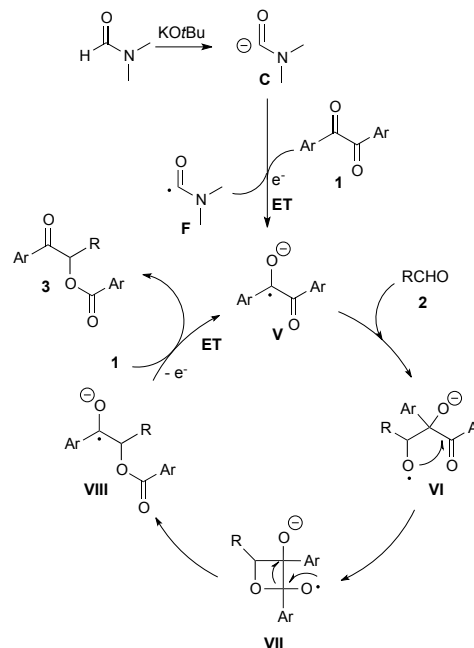


Fig. 5 EPR spectrum of a DMF solution containing KOtBu (0.125 M) and PBN (0.5 M) (black line). EPR spectrum of the paramagnetic adduct [PBN-benzil anion radical **V**][•] obtained upon addition of benzil **1a** (0.5 M) (red line).

Furthermore, the same EPR spectrum for the trapped radical anion **V** was also detected with a mixture of KOtBu-DMF, benzil **1a**, and aldehyde **2a**. Assuming that the use of an excess of spin trap warrants a constant amount of trapped species,²⁷ the intensities of the EPR signal of **V** in the presence or absence of **2a** were compared. Interestingly, it was noticed that the addition of aldehyde **2a** produced an appreciable lowering of signal intensity over the time (Figure S4), thus suggesting a competition between **2a** and PBN for the radical anion **V**. Overall, these results are consistent with the possible

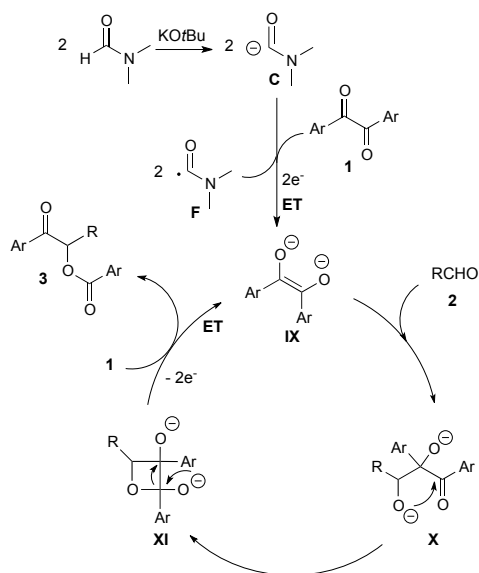
generation of the benzil anion radical **V** via single ET from the carbamoyl anion **C**, followed by its addition to the aldehyde **2** to give the oxygen radical **VI**, which then rearranges to the radical reducing species **VIII** through the cyclic intermediate **VII** (Scheme 5). In agreement with this proposal, the EPR signal of Figure 4 (dashed line) could be assigned to one of the intermediates **VI-VIII**; these are all quite long-lived radicals that do not present hyperfine coupling with the unpaired electron. On the other hand, the benzil anion radical **V** has been described as a highly unstable and short-lived radical species,²⁶ thus explaining the absence of signal in the experiment carried out without the spin trap.



Scheme 5 Plausible radical pathway for the cross-benzoin-like reaction of benzils **1** with aldehydes **2**.

With this information in hand, we turned back to the preparative **1a/2a** coupling and, surprisingly, we found that it was inhibited to a very limited extent by the addition (3 equiv.) of the radical scavengers TEMPO (**3aa**: 87%) and PBN (**3aa**: 81%) with no clear evidence of trapped products (see the ESI). This result seems to indicate that the proposed radical pathway could only minimally contribute to the overall process of **3aa** synthesis. Therefore, as a further possibility we considered the potential formation of the enediolate anion **IX** by two sequential ET steps from the carbamoyl anion **C** to benzil **1a** (Scheme 6). It is worth noting that intermediates of types **IX** have been previously generated by reduction of benzils with metal alkali,²⁸ SmI_2 ,²⁹ and by electrochemical methods.³⁰ The spontaneous disproportionation of the benzil anion radical **V** into benzil **1a** and the enediolate anion **IX** has been also proposed.³¹ Accordingly, we calculated the energetics of the benzil **1a**/benzaldehyde **2g** coupling by the supposed dianionic pathway of Scheme 6.³² The free energy stabilization of the initial two electron-transfer process from **C** to **1a** was investigated by treating reactants and products

separately. Following this model,³³ the first ET to form the benzil anion radical **V** was found to be exergonic by 2.4 kcal mol⁻¹, while the second ET furnishing the reactive enediolate anion **IX** was endergonic by 23.0 kcal mol⁻¹. In parallel, the disproportionation of the benzil anion radical **V** into benzil **1a** and the dianion **IX** was also calculated using the same thermodynamic ET model and found to be endergonic by 26.3 kcal mol⁻¹.



Scheme 6 Hypothesized dianionic pathway for the cross-benzoin-like reaction of benzils **1** with aldehydes **2**.

It is important to stress that these are only qualitative values that can be quite different from the experimental ones; it is well known, in fact, that this model suffers from the difficult identification of a realistic donor-acceptor complex.³³ The subsequent coupling of dianion **IX** with benzaldehyde **2g** to form the cyclic intermediate **XI** through the first adduct **X** proceeded with an energy barrier of 17.6 kcal mol⁻¹ (see the energy profile of Figure 6). Remarkably, the final two ET step from **XI** to **1a** forming the dianion **IX** and the product **3ag** resulted to be exergonic by 18.5 kcal mol⁻¹, thus supporting the hypothesis of a chain process promoted by the regenerated dianion **IX**.

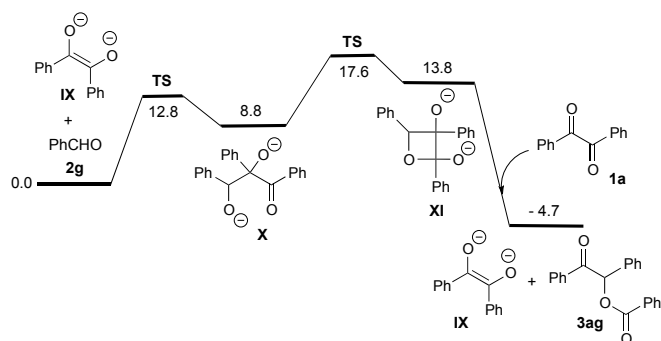
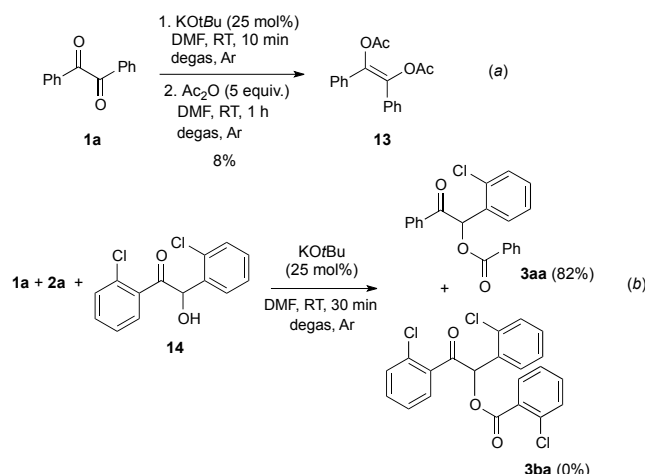


Fig. 6 Calculated ($\Delta\Delta G$ kcal mol⁻¹) energies for the dianionic pathway of **1a/2g** coupling in DMF [M06//6-31+G(d,p) level using the PCM continuum model; see ESI for details].

Since lower absolute values of reduction potentials are expected for benzils **1** displaying electron-withdrawing groups, the proposed mechanistic hypothesis appeared to be consistent with the reactivity order observed in the substrate scope study (Table 2, entries 1-9 vs. entry 10).

In order to confirm our assumption that the enediolate anion **IX** is the key intermediate of the **1/2** condensation with the KOtBu-DMF system, a trapping experiment was attempted by quenching the duly deaerated (Ar atmosphere) deep-blue DMF solution of benzil **1a** and KOtBu (25 mol%) with an excess (5 equiv.) of acetic anhydride. Very satisfyingly, the expected O,O'-diacetyl-1,2-diphenylethen-1,2-diol **13** could be recovered in 8% yield with almost exclusive (*Z*)-configuration (Scheme 7, eqn. *a*). Of note, the presence of oxygen in the reaction mixture precluded the isolation of **13**, thus accounting for the observed low reaction rate of the **1/2** coupling under aerated conditions (Table 1, entry 3); on the other hand, the oxidation by oxygen of the enediolate anion **IX** to benzil has been reported as a fast reaction.²⁸ A crossover experiment was also performed to exclude the possible generation of dianion **IX** by deprotonation of eventually formed benzoin. Accordingly, **1a** and **2a** were reacted in the presence of the substituted benzoin **14** (1 equiv.) observing the formation of the target adduct **3aa** without any evidence of the crossover product **3ba** (eqn. *b*).



Scheme 7. Trapping of the postulated enediolate anion **IX** and crossover experiment.

At this stage of our study, we could not exclude a similar dianionic pathway for the KOtBu-DMSO system as well.¹⁴ The initial two ET process from benzil **1a** leading to the enediolate **IX** was calculated to be endergonic by 50.5 kcal mol⁻¹, being the first ET endergonic by 11.2 kcal mol⁻¹. Although a case-by-case approach should be considered depending on the stereoelectronic features of the diketone and aldehyde substrates, these preliminary calculations indicated that the ET-based mechanism is a low probability activation mode of benzil in DMSO. Hence, the ionic route mediated by dimsilyl carbanion **A** (Scheme 1) was calculated for the activation of **1a** resulting in the energy profile of Figure 7. The first adduct **I(A)** was found 17.3 kcal mol⁻¹ lower in energy than the reactants with an activation energy of 5.3 kcal mol⁻¹. The rearrangement

to form the epoxide **II(A)** and then the carbanion **III(A)** proceeded with energy barriers of 8.6 and 10.4 kcal mol⁻¹, respectively. In situations such as this, it is likely that the forward reaction leading to the product **3** would be favored in a competition with the reverse reaction dissociating back to the separated reactants **1** and **A**.

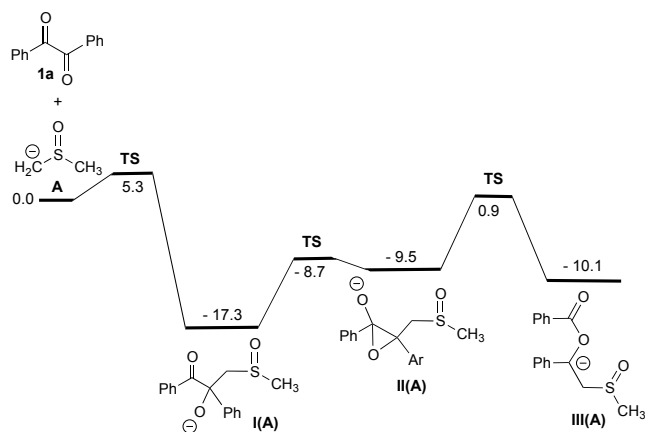


Fig. 7 Calculated ($\Delta\Delta G$ kcal mol⁻¹) energy profile of the ionic pathway of Scheme 1 with the postulated promoter **A** (dimesyl anion) [M06//6-31+G(d,p) level using the PCM continuum model; see ESI for details].

Conclusions

In summary, we have developed benzoin- and Stetter-like reactions of α -diketone donors with aromatic aldehyde and chalcone acceptors, respectively, mediated by KOtBu-DMF. Condensations proceeded under mild conditions with good efficiency and high level of chemoselectivity. From a mechanistic point of view, following the evaluation of plausible ionic and radical routes, the experimental results and calculations supported a dianionic pathway involving the formation of the enediolate anion derived from benzil as the key step. This intermediate is proposed to be generated by double electron-transfer to benzil from the carbamoyl anion of DMF that is the crucial initiator of the umpolung process.²² This activation mode of benzils resulted to be different from that operating with the KOtBu-DMSO system, for which calculations suggested the ionic route also proposed for cyanide catalysis. It is important to stress, however, that the formulation of a more complex mechanistic picture that unites polar and radical steps cannot be excluded for both KOtBu-DMF and KOtBu-DMSO systems and should be evaluated on the basis of the substitution pattern of the donor/acceptor substrates. This aspect of our mechanistic proposal will be clarified in future work and complemented by further investigation on new modes of reactivity enabled by ET processes to benzils under homogeneous and heterogeneous conditions.

Experimental Section

General Information

Potassium *tert*-butoxide was purified by sublimation (200–220 °C at 1 mmHg) before utilization. Reactions were monitored by TLC on silica gel 60 F₂₅₄ with detection by charring with phosphomolybdic acid. Flash column chromatography was performed on silica gel 60 (230–400 mesh). ¹H (300 MHz), ¹³C (75 MHz), and ¹⁹F (282 MHz) NMR spectra were recorded in CDCl₃ solutions at room temperature. Peaks assignments were aided by ¹H-¹H COSY and gradient-HMQC experiments. ESI-MS routine analyses were performed in positive ion mode with samples dissolved in 10 mM solution of ammonium formate in 1:1 MeCN/H₂O. For accurate mass measurements, the compounds were detected in positive ion mode by HPLC-Chip Q/TOF-MS (nanospray) analysis using a quadrupole, a hexapole, and a time-of-flight unit to produce spectra. Elemental analyses were performed with FLASH 2000 Series CHNS/O analyzer (ThermoFisher Scientific). Liquid aldehydes were freshly distilled before their utilization. Diketones **1a**, **1b**, **1d**, chalcones **4a-c** are commercially available compounds. Diketone **1c**,³⁴ chalcones **4d-f**,³⁵ and compound **9**¹⁸ were synthesized as described. Spectroscopic data of compounds **3aa**,^{14a} **3ac**,^{14a} **3ae**,^{14a} **3af**,^{14a} **3ag**,^{14a} **3da**,^{14a} **3ab**,^{14b} **3ad**,^{14b} **3ch**,^{14b} **5aa**,¹⁶ **5ab**,¹⁶ **5ac**,¹⁶ **5ad**,¹⁶ **5ae**,¹⁶ **5af**,¹⁶ **5ca**,¹⁶ **5db**¹⁶ were identical to those previously reported.

Optimization of the model cross-benzoin-type reaction of benzil **1a** with *o*-chlorobenzaldehyde **2a** (Table 1).

Entries 1–2. To a vigorously stirred solution of benzil **1a** (105 mg, 0.50 mmol) and *o*-chlorobenzaldehyde **2a** (56 μ L, 0.50 mmol) in anhydrous DMF (1 mL), the stated amount of potassium *tert*-butoxide (mol% based on **1a**) was added in one portion. The mixture was degassed under vacuum and saturated with argon (by an argon-filled balloon) three times. The reaction mixture was stirred at room temperature for the stated reaction time, then diluted with H₂O (5 mL) and extracted with Et₂O (2 \times 25 mL); the combined organic phases were dried (Na₂SO₄), concentrated, and eluted from a column of silica gel with 20:1 cyclohexane-AcOEt to give **3aa**.

Entry 3. To a vigorously stirred solution of benzil **1a** (105 mg, 0.50 mmol) and *o*-chlorobenzaldehyde **2a** (56 μ L, 0.50 mmol) in anhydrous DMF (1 mL), potassium *tert*-butoxide (14 mg, 0.125 mmol) was added in one portion. The reaction mixture was stirred under open air at room temperature for 16 h, then diluted with H₂O (5 mL) and extracted with Et₂O (2 \times 25 mL); the combined organic phases were dried (Na₂SO₄), concentrated, and eluted from a column of silica gel with 20:1 cyclohexane-AcOEt to give **3aa**.

Entries 4–8. To a vigorously stirred solution of benzil **1a** (105 mg, 0.50 mmol) and *o*-chlorobenzaldehyde **2a** (56 μ L, 0.50 mmol) in anhydrous DMF (1 mL), the stated amount of base (25 mol% based on **1a**) was added in one portion. The mixture was degassed under vacuum and saturated with argon (by an argon-filled balloon) three times. The reaction mixture was stirred at room temperature for the stated reaction time, then diluted with H₂O (5 mL) and extracted with Et₂O (2 \times 25 mL);

the combined organic phases were dried (Na_2SO_4), concentrated, and eluted from a column of silica gel with 20:1 cyclohexane-AcOEt to give **3aa**.

Entries 9-12. To a vigorously stirred solution of benzil **1a** (105 mg, 0.50 mmol) and *o*-chlorobenzaldehyde **2a** (56 μL , 0.50 mmol) in the stated anhydrous solvent (1 mL), potassium *tert*-butoxide (14 mg, 0.125 mmol) was added in one portion. The mixture was degassed under vacuum and saturated with argon (by an argon-filled balloon) three times. The reaction mixture was stirred at room temperature for the stated reaction time, then diluted with H_2O (5 mL) and extracted with Et_2O (2×25 mL); the combined organic phases were dried (Na_2SO_4), concentrated, and eluted from a column of silica gel with 20:1 cyclohexane-AcOEt to give **3aa**. Product **3aa** was detected and isolated just in the case of entry 12.

Entries 13-14. To a vigorously stirred solution of benzil **1a** (105 mg, 0.50 mmol), *o*-chlorobenzaldehyde **2a** (56 μL , 0.50 mmol) and the stated amount of anhydrous DMF in anhydrous THF (1 mL), potassium *tert*-butoxide (14 mg, 0.125 mmol) was added in one portion. The mixture was degassed under vacuum and saturated with argon (by an argon-filled balloon) three times. The reaction mixture was stirred at room temperature for 16 h, then diluted with H_2O (5 mL) and extracted with Et_2O (2×25 mL); the combined organic phases were dried (Na_2SO_4), concentrated, and eluted from a column of silica gel with 20:1 cyclohexane-AcOEt to give **3aa**.

General procedure for the cross-benzoin-type reactions of α -diketones **1** with aldehydes **2** mediated by KO^tBu-DMF (Table 2).

To a vigorously stirred solution of α -diketone **1** (1.00 mmol) and aldehyde **2** (1.00 mmol) in anhydrous DMF (2 mL), potassium *tert*-butoxide (28 mg, 0.25 mmol) was added in one portion. The mixture was degassed under vacuum and saturated with argon (by an argon-filled balloon) three times. The reaction mixture was stirred at room temperature until complete disappearance or best conversion of reactants was detected (TLC analysis, ~1-16 h), then diluted with H_2O (10 mL) and extracted with Et_2O (2×50 mL). The combined organic phases were dried (Na_2SO_4), concentrated, and eluted from a column of silica gel with the suitable elution system to give the benzoylated benzoin **3**.

1-(2-Chlorophenyl)-2-oxo-2-phenylethyl benzoate (**3aa**).

Column chromatography with 20:1 cyclohexane-AcOEt afforded **3aa**^{14a} (333 mg, 95%) as a white foam. ¹H NMR (300 MHz, CDCl_3): δ = 8.12–8.07 (m, 2 H, Ar), 8.02–7.98 (m, 2 H, Ar), 7.60–7.40 (m, 8 H, Ar), 7.44 (s, 1 H, H-1), 7.36–7.24 (m, 2 H, Ar); ¹³C{¹H} NMR (75 MHz, CDCl_3): δ = 193.3, 165.8, 134.9, 134.4, 134.2, 133.8, 133.4, 131.8, 130.8, 130.4, 130.2, 130.1, 130.0, 129.9, 129.5, 129.2, 129.0, 128.8, 128.4, 127.6, 74.0.

1-(2-Methoxyphenyl)-2-oxo-2-phenylethyl benzoate (**3ab**).

Column chromatography with 20:1 cyclohexane-AcOEt afforded **3ab**^{14b} (311 mg, 90%) as a white amorphous solid. ¹H NMR (300 MHz, CDCl_3): δ = 8.15–8.07 (m, 2 H, Ar), 8.08–7.99 (m, 2 H, Ar), 7.59 (s, 1 H, H-1), 7.58–7.49 (m, 2 H, Ar), 7.49–7.38

(m, 5 H, Ar), 7.38–7.30 (m, 1 H, Ar), 7.01–6.90 (m, 2 H, Ar), 3.92 (s, 3 H, CH_3); ¹³C{¹H} NMR (75 MHz, CDCl_3): δ = 194.0, 166.2, 156.7, 134.7, 133.4, 133.2, 130.8, 130.0, 129.9, 129.7, 128.7, 128.5, 128.35, 122.3, 121.2, 111.3, 71.6, 55.8.

2-Oxo-2-phenyl-1-(*o*-tolyl)ethyl benzoate (**3ac**).

Column chromatography with 12:1 cyclohexane-AcOEt afforded **3ac**^{14a} (155 mg, 47%) as a white amorphous solid. ¹H NMR (300 MHz, CDCl_3): δ = 8.14–8.08 (m, 2 H, Ar), 7.92–7.86 (m, 2 H, Ar), 7.60–7.7.37 (m, 8 H, Ar), 7.32–7.14 (m, 2 H), 7.29 (s, 1 H, H-1), 2.50 (s, 3 H, CH_3); ¹³C{¹H} NMR (75 MHz, CDCl_3): δ = 194.2, 166.1, 137.3, 135.0, 133.4, 133.3, 132.3, 131.3, 130.0–128.4 (11 C), 126.7, 75.6, 19.5.

1-(3-Bromophenyl)-2-oxo-2-phenylethyl benzoate (**3ad**).

Column chromatography with 20:1 cyclohexane-AcOEt afforded **3ad**^{14b} (363 mg, 92%) as a white amorphous solid. ¹H NMR (300 MHz, CDCl_3): δ = 8.16–8.07 (m, 2 H, Ar), 8.03–7.94 (m, 2 H, Ar), 7.76–7.69 (m, 1 H, Ar), 7.62–7.52 (m, 2 H, Ar), 7.51–7.38 (m, 6 H, Ar), 7.30–7.24 (m, 1 H, Ar), 7.04 (s, 1 H, H-1); ¹³C{¹H} NMR (75 MHz, CDCl_3): δ = 193.2, 165.8, 135.89, 134.4, 133.8, 133.5, 132.5, 131.5, 130.6, 130.0, 129.3, 129.1, 128.8, 128.5, 127.2, 123.1, 76.9.

1-(4-Chlorophenyl)-2-oxo-2-phenylethyl benzoate (**3ae**).

Column chromatography with 20:1 cyclohexane-AcOEt gave first 2-(4-chlorophenyl)-2-oxo-1-phenylethyl benzoate **3'ae**^{14a} (59 mg, 17%) as a white amorphous solid. ¹H NMR (300 MHz, CDCl_3): δ = 8.14–8.08 (m, 2 H, Ar), 7.94–7.90 (m, 2 H, Ar), 7.60–7.50 (m, 2 H, Ar), 7.48–7.32 (m, 8 H, Ar), 7.03 (s, 1 H, H-1); ¹³C NMR (75 MHz, CDCl_3): δ = 192.6, 166.0, 133.5, 130.2–128.5 (17 C), 77.9. Eluted second was **3ae**^{14a} (266 mg, 76%) as a white amorphous solid. ¹H NMR (300 MHz, CDCl_3): δ = 8.14–8.06 (m, 2 H, Ar), 8.00–7.94 (m, 2 H, Ar), 7.60–7.32 (m, 10 H, Ar), 7.06 (s, 1 H, H-1); ¹³C{¹H} NMR (75 MHz, CDCl_3): δ = 193.4, 165.9, 135.4, 134.5, 133.7, 133.5, 130.0–128.4 (14 C), 77.3.

1-(2,3-Dichlorophenyl)-2-oxo-2-phenylethyl benzoate (**3af**).

Column chromatography with 50:1 cyclohexane-AcOEt afforded **3af**^{14a} (308 mg, 80%) as a white amorphous solid. ¹H NMR (300 MHz, CDCl_3): δ = 8.12–8.04 (m, 2 H, Ar), 8.02–7.94 (m, 2 H, Ar), 7.62–7.53 (m, 2 H, Ar), 7.61 (s, 1 H, H-1), 7.52–7.39 (m, 6 H, Ar), 7.22 (t, 1 H, J = 8.0 Hz, Ar); ¹³C{¹H} NMR (75 MHz, CDCl_3): δ = 193.2, 165.8, 134.5, 134.2, 133.8, 132.4, 131.7, 130.3, 129.1–128.1 (12 C), 74.5.

2-Oxo-1,2-diphenylethyl benzoate (**3ag**).

Column chromatography with 10:1 cyclohexane-AcOEt afforded **3ag**^{14a} (161 mg, 51%) as a white amorphous solid. ¹H NMR (300 MHz, CDCl_3): δ = 8.14–8.08 (m, 2 H, Ar), 8.02–7.94 (m, 2 H, Ar), 7.60–7.50 (m, 4 H, Ar), 7.48–7.34 (m, 7 H, Ar), 7.08 (s, 1 H, H-1); ¹³C{¹H} NMR (75 MHz, CDCl_3): δ = 193.7, 166.0, 134.7, 133.7, 133.5, 133.4, 130.0, 129.3, 129.1–128.4 (12 C), 77.9.

1,2-bis(2-chlorophenyl)-2-oxoethyl 2-chlorobenzoate (**3ba**).

Column chromatography with 18:1 cyclohexane-AcOEt afforded **3ba** (327 mg, 78%) as a white amorphous solid. ^1H NMR (300 MHz, CDCl_3): δ = 8.06-7.99 (m, 1 H, Ar), 7.76-7.69 (m, 1 H, Ar), 7.75-7.58 (m, 1 H, Ar), 7.47-7.44 (m, 3 H, Ar + H-1), 7.38-7.32 (m, 4 H, Ar), 7.32-7.27 (m, 3 H, Ar); $^{13}\text{C}\{^1\text{H}\}$ NMR (75 MHz, CDCl_3): δ = 194.7, 164.4, 136.2, 134.4, 134.3, 133.1, 132.3, 132.1, 131.7, 131.2, 130.8, 130.5, 130.3, 130.0, 129.5, 128.6, 127.3, 126.7, 126.6, 76.8; elemental analysis calcd (%) for $\text{C}_{21}\text{H}_{13}\text{Cl}_3\text{O}_3$: C 60.10, H 3.12; found: C 60.54, H 3.23.

1-(2-Bromophenyl)-2-oxo-2-(4-(trifluoromethyl)phenyl)ethyl 4-(trifluoromethyl)benzoate (**3ch**).

Column chromatography with 30:1 cyclohexane-AcOEt afforded **3ch**^{14b} (360 mg, 68%) as a white foam. ^1H NMR (300 MHz, CDCl_3): δ = 8.24-8.18 (m, 2 H, Ar), 8.12-8.06 (m, 2 H, Ar), 7.74-7.68 (m, 5 H, Ar), 7.53 (s, 1 H, Ar), 7.46-7.41 (m, 1 H, Ar), 7.39-7.22 (m, 2 H, Ar); $^{13}\text{C}\{^1\text{H}\}$ NMR (75 MHz, CDCl_3): δ = 192.4, 164.7, 137.0, 135.7, 135.3, 135.2, 135.0, 134.9, 134.7, 134.0, 132.5, 132.3, 131.7, 130.7, 130.6, 129.2, 128.6, 127.5, 126.1, 126.0, 125.9, 125.8, 125.7, 125.6, 125.6, 125.4, 124.9, 124.8, 124.8, 122.3, 122.1, 76.8; ^{19}F NMR (282 MHz, CDCl_3): δ = -63.2 (s, 3 F, CF_3), -63.3 (s, 3 F, CF_3).

General procedure for the double C-arylation of activated alkenes **4** with α -diketones **1** mediated by KO t Bu-DMF (Table 3).

To a vigorously stirred solution of α -diketone **1** (1.00 mmol) and alkene **2** (0.50 mmol), in anhydrous DMF (2 mL), potassium *tert*-butoxide (112 mg, 1.00 mmol) was added in one portion. The mixture was degassed under vacuum and saturated with argon (by an argon-filled balloon) three times. The reaction mixture was stirred at room temperature until complete disappearance or best conversion of the starting alkene (TLC analysis, ca. 2-16 h), then diluted with H_2O (10 mL), and extracted with CH_2Cl_2 (2 \times 50 mL). The combined organic phases were washed with brine (15 mL), dried (Na_2SO_4), concentrated, and eluted from a column of silica gel with the suitable elution system to give **5**.

2-Benzoyl-1,3,4-triphenylbutane-1,4-dione (**5aa**).

Column chromatography with 10:1 cyclohexane-AcOEt afforded **5aa**¹⁶ (148 mg, 71%) as a white amorphous solid. ^1H NMR (300 MHz, CDCl_3): δ = 8.08-7.98 (m, 2 H, Ar), 7.95-7.89 (m, 2 H, Ar), 7.70-7.65 (m, 2 H, Ar), 7.54-7.44 (m, 2 H, Ar), 7.43-7.32 (m, 4 H, Ar), 7.31-7.21 (m, 5 H, Ar), 7.14-7.06 (m, 2 H, Ar), 7.05-6.95 (m, 1 H, Ar), 6.38 (d, J = 10.7 Hz, 1 H, H-2), 5.80 (d, J = 10.7 Hz, 1 H, H-3); $^{13}\text{C}\{^1\text{H}\}$ NMR (75 MHz, CDCl_3): δ = 198.1, 195.9, 194.2, 136.6, 136.2, 135.9, 134.8, 133.4, 133.3, 133.1, 129.1, 129.0, 128.6, 128.5, 128.4, 127.8, 60.5, 55.2.

2-Benzoyl-3-(4-chlorophenyl)-1,4-diphenylbutane-1,4-dione (**5ab**).

Column chromatography with 13:1 cyclohexane-AcOEt afforded **5ab**¹⁶ (174 mg, 77%) as a white amorphous solid. ^1H NMR (300 MHz, CDCl_3): δ = 8.04-7.96 (m, 2 H, Ar), 7.94-7.87 (m, 2 H, Ar), 7.74-7.67 (m, 2 H, Ar), 7.54-7.44 (m, 3 H, Ar), 7.44-7.35 (m, 3 H, Ar), 7.35-7.27 (m, 3 H, Ar), 7.24-7.19 (m, 2 H, Ar),

7.12-7.03 (m, 2 H, Ar), 6.36 (d, J = 10.7 Hz, 1 H, H-2), 5.79 (d, J = 10.7 Hz, 1 H, H-3); $^{13}\text{C}\{^1\text{H}\}$ NMR (75 MHz, CDCl_3): δ = 197.8, 195.5, 194.0, 136.5, 136.1, 135.7, 133.8, 133.6, 133.5, 133.3, 130.3, 129.2, 129.0, 128.7, 128.7, 128.6, 60.4, 54.3.

2-Benzoyl-3-(4-bromophenyl)-1,4-diphenylbutane-1,4-dione (**5ac**).

Column chromatography with 13:1 cyclohexane-AcOEt afforded **5ac**¹⁶ (173 mg, 70%) as a white amorphous solid. ^1H NMR (300 MHz, CDCl_3): δ = 8.04-7.96 (m, 2 H, Ar), 7.95-7.88 (m, 2 H, Ar), 7.73-7.67 (m, 2 H, Ar), 7.53-7.43 (m, 3 H, Ar), 7.42-7.36 (m, 3 H, Ar), 7.35-7.27 (m, 3 H, Ar), 7.26-7.20 (m, 2 H, Ar), 7.18-7.12 (m, 2 H, Ar), 6.35 (d, J = 10.7 Hz, 1 H, H-2), 5.78 (d, J = 10.7 Hz, 1 H, H-3); $^{13}\text{C}\{^1\text{H}\}$ NMR (75 MHz, CDCl_3): δ = 197.8, 195.5, 194.0, 136.5, 136.1, 135.7, 134.0, 133.6, 133.5, 133.3, 132.2, 130.7, 129.0, 128.7, 128.7, 128.6, 122.0, 60.4, 54.4.

2-Benzoyl-1-(4-chlorophenyl)-3,4-diphenylbutane-1,4-dione (**5ad**).

Column chromatography with 10:1 cyclohexane-AcOEt afforded **5ad**¹⁶ (138 mg, 61%) as a 1:1 mixture of diastereoisomers. Separation of the two diastereoisomers was carried by a second column chromatography using toluene as the elution system. First eluted diastereoisomer: ^1H NMR (300 MHz, CDCl_3): δ = 8.05-7.96 (m, 2 H, Ar), 7.89-7.82 (m, 2 H, Ar), 7.66-7.58 (m, 2 H, Ar), 7.53-7.22 (m, 10 H, Ar), 7.14-7.08 (m, 2 H, Ar), 7.07-7.00 (m, 1 H, Ar), 6.31 (d, J = 10.7 Hz, 1 H, H-2), 5.78 (d, J = 10.7 Hz, 1 H, H-3); $^{13}\text{C}\{^1\text{H}\}$ NMR (75 MHz, CDCl_3): δ = 198.0, 195.6, 193.0, 139.9, 136.5, 135.8, 134.7, 134.5, 133.5, 133.2, 130.0, 129.1, 129.0, 129.0, 128.8, 128.6, 128.5, 128.4, 128.0, 127.8, 60.4, 55.3. Second eluted diastereoisomer: ^1H NMR (300 MHz, CDCl_3): δ = 8.05-7.96 (m, 2 H, Ar), 7.92-7.85 (m, 2 H, Ar), 7.66-7.58 (m, 2 H, Ar), 7.52-7.43 (m, 2 H, Ar), 7.41-7.32 (m, 4 H, Ar), 7.29-7.22 (m, 4 H, Ar), 7.18-7.08 (m, 2 H, Ar), 7.07-7.00 (m, 1 H, Ar), 6.31 (d, J = 10.7 Hz, 1 H, H-2), 5.77 (d, J = 10.7 Hz, 1 H, H-3); $^{13}\text{C}\{^1\text{H}\}$ NMR (75 MHz, CDCl_3): δ = 197.9, 194.8, 193.8, 139.9, 136.1, 135.8, 134.9, 134.7, 133.5, 133.2, 130.0, 129.2, 129.0, 128.9, 128.8, 128.7, 128.6, 128.5, 127.9, 60.4, 55.1.

2-Benzoyl-1-(4-methoxyphenyl)-3,4-diphenylbutane-1,4-dione (**5ae**).

Column chromatography with 6:1 cyclohexane-AcOEt afforded **5ae**¹⁶ (94 mg, 42%) as an inseparable 1:1 mixture of diastereoisomers. ^1H NMR (300 MHz, CDCl_3): δ = 8.05-7.98 (m, 2 H, Ar), 7.95-7.88 (m, 2 H, Ar), 7.73-7.64 (m, 2 H, Ar), 7.52-7.41 (m, 2 H, Ar), 7.41-7.32 (m, 4 H, Ar), 7.31-7.26 (m, 2 H, Ar), 7.15-7.06 (m, 2 H, Ar), 7.06-6.98 (m, 1 H, Ar), 6.85-6.69 (m, 2 H, Ar), 6.32 (d, J = 10.8 Hz, 0.5 H, H-2'), 6.31 (d, J = 10.8 Hz, 0.5 H, H-2''), 5.79 (d, J = 10.8 Hz, 0.5 H, H-3'), 5.78 (d, J = 10.8 Hz, 0.5 H, H-3''), 3.80 (s, 1.5 H, CH_3 '), 3.78 (s, 1.5 H, CH_3 ''); $^{13}\text{C}\{^1\text{H}\}$ NMR (75 MHz, CDCl_3): δ = 198.3 (0.5 C), 198.1 (0.5 C), 196.0 (0.5 C), 194.4 (0.5 C), 194.0 (0.5 C), 192.4 (0.5 C), 163.7 (0.5 C), 163.4 (0.5 C), 136.7, 136.2, 136.0, 134.9, 133.3, 133.2, 133.0, 131.1, 130.3, 129.7, 129.6, 129.0, 128.7, 128.6, 128.5, 128.4, 127.7, 113.8 (0.5 C), 113.6 (0.5 C), 60.4 (0.5 C), 60.2 (0.5 C), 55.4, 55.1 (0.5 C), 55.0 (0.5 C).

2-Benzoyl-3-(4-chlorophenyl)-1-(4-methoxyphenyl)-4-phenylbutane-1,4-dione (5af).

Column chromatography with 7:1 cyclohexane-AcOEt afforded **5af**¹⁶ (99 mg, 41%) as an inseparable 1:1 mixture of diastereoisomers. ¹H NMR (300 MHz, CDCl₃): δ = 8.03-7.95 (m, 2 H, Ar), 7.94-7.85 (m, 2 H, Ar), 7.76-7.68 (m, 2 H, Ar), 7.53-7.36 (m, 4 H, Ar), 7.35-7.17 (m, 4 H, Ar), 7.11-7.04 (m, 2 H, Ar), 6.84-6.73 (m, 2 H, Ar), 6.29 (d, *J* = 10.7 Hz, 0.5 H, H-2'), 6.28 (d, *J* = 10.7 Hz, 0.5 H, H-2''), 5.78 (d, *J* = 10.7 Hz, 0.5 H, H-3'), 5.76 (d, *J* = 10.7 Hz, 0.5 H, H-3''), 3.81 (s, 1.5 H, CH₃'), 3.78 (s, 1.5 H, CH₃''); ¹³C{¹H} NMR (75 MHz, CDCl₃): δ = 198.0 (0.5 C), 197.9 (0.5 C), 195.7 (0.5 C), 194.3 (0.5 C), 193.6 (0.5 C), 192.2 (0.5 C), 163.8 (0.5 C), 136.6, 136.2, 135.8, 133.8, 133.5, 133.4, 133.3, 131.1, 130.4, 130.3, 129.4, 129.2, 129.0, 128.6, 113.9 (0.5 C), 113.8 (0.5 C), 60.3 (0.5 C), 60.1 (0.5 C), 55.5 (0.5 C), 55.4 (0.5 C), 54.3 (0.5 C), 54.1 (0.5 C).

2-Benzoyl-3-phenyl-1,4-bis(4-(trifluoromethyl)phenyl)butane-1,4-dione (5ca).

Column chromatography with 16:1 cyclohexane-AcOEt afforded **5ca**¹⁶ (85 mg, 30%) as a 19:1 mixture of diastereoisomers. For the major isomer: ¹H NMR (300 MHz, CDCl₃): δ = 8.12-8.06 (m, 2 H, Ar), 8.02-7.96 (m, 2 H, Ar), 7.78-7.70 (m, 2 H, Ar), 7.69-7.58 (m, 4 H, Ar), 7.52-7.43 (m, 2 H, Ar), 7.32-7.27 (m, 2 H, Ar), 7.25-7.21 (m, 2 H, Ar), 7.16-7.10 (m, 2 H, Ar), 6.35 (d, *J* = 10.7 Hz, 1 H, H-2), 5.75 (d, *J* = 10.7 Hz, 1 H, H-3); ¹³C{¹H} NMR (75 MHz, CDCl₃): δ = 197.2, 195.2, 193.4, 138.7, 138.5, 136.2, 133.8, 130.5, 129.4, 129.3, 128.9, 128.6, 128.6, 128.3, 128.3, 126.5, 125.8, 125.7, 123.1 (q, *J* = 270 Hz, 2 CF₃), 60.5, 55.6; ¹⁹F NMR (282 MHz, CDCl₃): δ = -63.0, -63.2, -63.3, -63.4.

2-Hydroxy-N,N-dimethyl-2-phenylacetamide (6).

Benzaldehyde (0.31 mL, 3.00 mmol) and DMF (0.23 mL, 3.00 mmol) were dissolved in anhydrous THF (7.5 mL) and stirred vigorously. To this cooled (-70 °C) solution, it was added a lithium diisopropylamine solution (0.56 M, 5.34 mL, 3.00 mmol), which in turn was freshly prepared from diisopropylamine (0.96 mL, 6.85 mmol) and *n*-butyllithium (2.0 M solution in *n*-hexane, 3.30 mL, 6.60 mmol) in anhydrous THF (7.5 mL) and precooled to -70 °C. The reaction mixture was stirred for 5 h at -70 °C, then allowed to reach room temperature and quenched with saturated aqueous NH₄Cl solution (2.5 mL). The organic phase was separated, dried (Na₂SO₄), concentrated, and eluted from a column of silica gel with 3.5:1 cyclohexane-AcOEt to separate apolar compounds, and then with 10:1 AcOEt-MeOH to afford **6**³⁶ (242 mg, 45%) as a white amorphous solid. ¹H NMR (300 MHz, CDCl₃): δ = 7.40-7.28 (m, 5 H, Ar), 5.18 (d, *J* = 4.9 Hz, 1 H, H-2), 4.75 (d, *J* = 4.9 Hz, 1 H, OH), 3.02 (s, 3 H, CH₃), 2.76 (s, 3 H, CH₃); ¹³C{¹H} NMR (75 MHz, CDCl₃): δ = 172.4, 139.2, 129.1, 128.6, 127.6, 71.6, 36.5, 36.4; elemental analysis calcd (%) for C₁₀H₁₃NO₂: C 67.02, H 7.31, N 7.82; found: C 67.61, H 7.02, N 7.48.

2-(Dimethylamino)-2-oxo-1-phenylethyl benzoate (7).

To a vigorous stirred solution of **6** (0.14 g, 0.80 mmol), pyridine (1.25 mL) and benzoyl chloride (1.20 mmol, 0.14 mL) DMAP (4.9 mg, 0.04 mmol) was added in one portion. The reaction mixture was stirred at room temperature under Ar atmosphere for 16 h. The mixture was then concentrated and eluted from a column of silica gel with 2.5:1 cyclohexane-AcOEt to afford **7** (158 mg, 70%) as a white amorphous solid. ¹H NMR (300 MHz, CDCl₃): δ = 8.11-8.07 (m, 2 H, Ar), 7.60-7.50 (m, 3 H, Ar), 7.45-7.38 (m, 5 H, Ar), 6.45 (s, 1 H, H-1), 3.03 (s, 3 H, CH₃), 2.99 (s, 3 H, CH₃); ¹³C{¹H} NMR (75 MHz, CDCl₃): δ = 168.0, 166.3, 134.2, 133.3, 130.1, 129.6, 129.4, 129.1, 128.6, 128.4, 73.8, 36.9, 36.2; elemental analysis calcd (%) for C₁₇H₁₇NO₃: C 72.07, H 6.05, N 4.49; found: C 72.64, H 5.86, N 4.07.

3-(2-chlorophenyl)-2,3-dihydroxy-N,N-dimethyl-2-phenylpropanamide (8).

To a vigorously stirred solution of **7** (45 mg, 0.16 mmol) and *o*-chlorobenzaldehyde **2a** (182 μL, 0.16 mmol) in anhydrous DMF (1 mL), potassium *tert*-butoxide (18 mg, 0.16 mmol) was added in one portion. The mixture was degassed under vacuum and saturated with argon (by an argon-filled balloon) three times. The reaction was stirred at room temperature for 16 h, then diluted with saturated NH₄Cl (2 mL) and extracted with Et₂O (10 mL × 2). The combined organic phases were dried (Na₂SO₄), concentrated, and eluted from a column of silica gel with 5:1 cyclohexane-AcOEt to separate apolar compounds, and then with 10:1 AcOEt-MeOH to afford **8** (11 mg, 22%) as a white amorphous solid. ¹H NMR (300 MHz, CDCl₃): δ = 7.67-7.62 (m, 1 H, Ar), 7.24-7.06 (m, 5 H, Ar), 7.04-6.96 (m, 3 H, Ar), 6.10 (d, *J* = 3.7 Hz, 1 H, H-3), 4.19 (d, *J* = 3.7 Hz, 1 H, OH-3), 3.94 (s, 1 H, OH-2), 3.01 (s, 3 H, CH₃), 2.70 (s, 3 H, CH₃); ¹³C{¹H} NMR (75 MHz, CDCl₃): δ = 173.8, 137.0, 134.9, 134.3, 129.9, 128.8, 128.6, 127.9, 127.8, 126.1, 125.5, 82.5, 73.6, 38.2, 37.1; elemental analysis calcd (%) for C₁₇H₁₈ClNO₃: C 63.85, H 5.67, N 4.38; found: C 63.34, H 5.89, N 4.89.

Coupling of nitrile 9 with o-chlorobenzaldehyde 2a (Scheme 2).

To a vigorously stirred solution of **9**¹⁸ (38 mg, 0.16 mmol) and *o*-chlorobenzaldehyde **2a** (182 μL, 0.16 mmol) in anhydrous DMF (1 mL), potassium *tert*-butoxide (18 mg, 0.16 mmol) was added in one portion. The mixture was degassed under vacuum and saturated with argon (by an argon-filled balloon) three times. The reaction was stirred at room temperature for 16 h, then diluted with saturated NH₄Cl (2 mL) and extracted with Et₂O (10 mL × 2). The combined organic phases were dried (Na₂SO₄), concentrated, and eluted from a column of silica gel with 20:1 cyclohexane-AcOEt to give **3aa** (36 mg, 65%) as a white foam.

2-Hydroxy-N,N-dimethyl-2,2-diphenylacetamide (12).

Benzophenone **11** (0.55 g, 3.00 mmol) and DMF (0.23 mL, 3.00 mmol) were dissolved in anhydrous THF (7.5 mL) and stirred vigorously. To this cooled (-70 °C) solution, it was added a lithium diisopropylamine solution (0.56 M, 5.34 mL, 3.00 mmol), which in turn was freshly prepared from

diisopropylamine (0.96 mL, 6.85 mmol) and *n*-butyllithium (2.0 M solution in *n*-hexane, 3.30 mL, 6.60 mmol) in anhydrous THF (7.5 mL) and precooled to -70 °C. The reaction mixture was stirred for 5 h at -70 °C, then allowed to reach room temperature and quenched with saturated aqueous NH₄Cl solution (2.5 mL). The organic phase was separated, dried (Na₂SO₄), concentrated, and eluted from a column of silica gel with 5:1 cyclohexane-AcOEt to afford **12** (574 mg, 70%) as a white amorphous solid. ¹H NMR (300 MHz, CDCl₃): δ = 7.38-7.30 (m, 10 H, Ar), 6.00 (s, 1 H, OH), 3.11 (bs, 3 H, CH₃), 2.55 (bs, 3 H, CH₃); ¹³C{¹H} NMR (75 MHz, CDCl₃): δ = 173.6, 141.7, 128.4, 128.3, 128.0, 80.8, 39.5, 38.0; elemental analysis calcd (%) for C₁₆H₁₇NO₂: C 75.27, H 6.71, N 5.49; found: C 75.68, H 6.38, N 5.83.

Coupling of benzil **1a** with *o*-chlorobenzaldehyde **2a** mediated by **D** (Scheme 3).

Compound **12** (76 mg, 0.30 mmol) was dissolved in anhydrous NMP (0.5 mL). The reaction mixture was cooled to 0 °C and then NaH (60% mineral dispersion, 14 mg, 0.36 mmol) was added in one portion. The resulting mixture was degassed under vacuum and saturated with argon (by an argon-filled balloon) three times. The mixture was allowed to reach room temperature and after 30 minutes was added dropwise by cannula to a degassed (Ar atmosphere) solution of benzil **1a** (62 mg, 0.30 mmol) and *o*-chlorobenzaldehyde **2a** (33 μL, 0.30 mmol) in NMP (0.5 mL). The mixture was stirred at room temperature for 16 h then diluted with saturated NH₄Cl (1 mL) and extracted with Et₂O (5 mL × 2). The combined organic phases were dried (Na₂SO₄), concentrated, and eluted from a column of silica gel with 20:1 cyclohexane-AcOEt; TLC and NMR analysis did not reveal the formation of the target product **3aa**.

Coupling of benzil **1a** with *o*-chlorobenzaldehyde **2a** in the presence of the radical scavenger TEMPO.

To a vigorously stirred solution of benzil **1a** (105 mg, 0.50 mmol), *o*-chlorobenzaldehyde **2a** (56 μL, 0.50 mmol) and 2,2,6,6-tetramethylpiperidine 1-oxyl (TEMPO) (235 mg, 1.50 mmol) in anhydrous DMF (1 mL), potassium *tert*-butoxide (14 mg, 0.125 mmol) was added in one portion. The mixture was degassed under vacuum and saturated with argon (by an argon-filled balloon) three times. The reaction mixture was stirred at room temperature for 30 min, then diluted with H₂O (5 mL) and extracted with Et₂O (2 × 25 mL); the combined organic phases were dried (Na₂SO₄), concentrated, and eluted from a column of silica gel with 20:1 cyclohexane-AcOEt to give **3aa** (152 mg, 87%).

Coupling of benzil **1a** with *o*-chlorobenzaldehyde **2a** in the presence of the radical scavenger PBN.

To a vigorously stirred solution of benzil **1a** (105 mg, 0.50 mmol), *o*-chlorobenzaldehyde **2a** (56 μL, 0.50 mmol) and *N*-*tert*-butyl- α -phenyl nitron (PBN) (266 mg, 1.50 mmol) in anhydrous DMF (1 mL), potassium *tert*-butoxide (14 mg, 0.125 mmol) was added in one portion. The mixture was degassed under vacuum and saturated with argon (by an argon-filled

balloon) three times. The reaction mixture was stirred at room temperature for 30 min, then diluted with H₂O (5 mL) and extracted with Et₂O (2 × 25 mL); the combined organic phases were dried (Na₂SO₄), concentrated, and eluted from a column of silica gel with 20:1 cyclohexane-AcOEt to give **3aa** (142 mg, 81%).

(**Z**)-1,2-Diphenylethene-1,2-diyl diacetate (**13**).

To a vigorously stirred solution of benzil **1a** (210 mg, 1.00 mmol) in anhydrous DMF (2 mL), potassium *tert*-butoxide (28 mg, 0.25 mmol) was added in one portion. The mixture was degassed under vacuum and saturated with argon (by an argon-filled balloon) three times. After 10 minutes acetic anhydride (0.47 mL, 5.00 mmol) was added in one portion (rapid change of color was observed). The reaction mixture was stirred at room temperature for 1 h, then diluted with H₂O (5 mL) and extracted with Et₂O (2 × 25 mL); the combined organic phases were dried (Na₂SO₄), concentrated, and eluted from a column of silica gel with 7:1 cyclohexane-AcOEt to give **13** as a white amorphous solid (23 mg, 8%). ¹H NMR (300 MHz, CDCl₃): δ = 7.30-7.16 (m, 10 H, Ar), 2.21 (s, 6 H, CH₃); ¹³C{¹H} NMR (75 MHz, CDCl₃): δ = 168.1, 138.5, 133.0, 128.8, 128.8, 128.2, 20.7; elemental analysis calcd (%) for C₁₈H₁₆O₄: C 72.96, H 5.44; found: C 72.56, H 5.88.

Crossover experiment (Scheme 7).

To a vigorously stirred solution of benzil **1a** (105 mg, 0.50 mmol), *o*-chlorobenzaldehyde **2a** (56 μL, 0.50 mmol), substituted benzoin **14** (140 mg, 0.50 mmol) in anhydrous DMF (1 mL), potassium *tert*-butoxide (14 mg, 0.125 mmol) was added in one portion. The mixture was degassed under vacuum and saturated with argon (by an argon-filled balloon) three times. The reaction mixture was stirred at room temperature for 30 min, then diluted with H₂O (5 mL) and extracted with Et₂O (2 × 25 mL); the combined organic phases were dried (Na₂SO₄), concentrated, and eluted from a column of silica gel with 20:1 cyclohexane-AcOEt to give **3aa** (143 mg, 82%) as the only isolable product.

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Electronic Supporting Information

Cross-Benzoin and Stetter-Type Reactions Mediated by KO^tBu-DMF via Electron-Transfer process

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Mass spectrometric experiments

The mass spectrometric investigations were carried out on a LCQ Duo (ThermoQuest, San Jose, CA, USA), equipped with an electrospray ionization source operating in negative-ion mode. Instrumental parameters: capillary voltage -10 V, spray voltage 4.50 kV, capillary temperature of 150 °C, mass scan range from m/z 50 to 1200; N_2 was used as sheath gas. The samples were injected into the spectrometer by a syringe pump at a constant flow rate of 8 $\mu\text{L}/\text{min}$ using the appropriate eluting solvent.

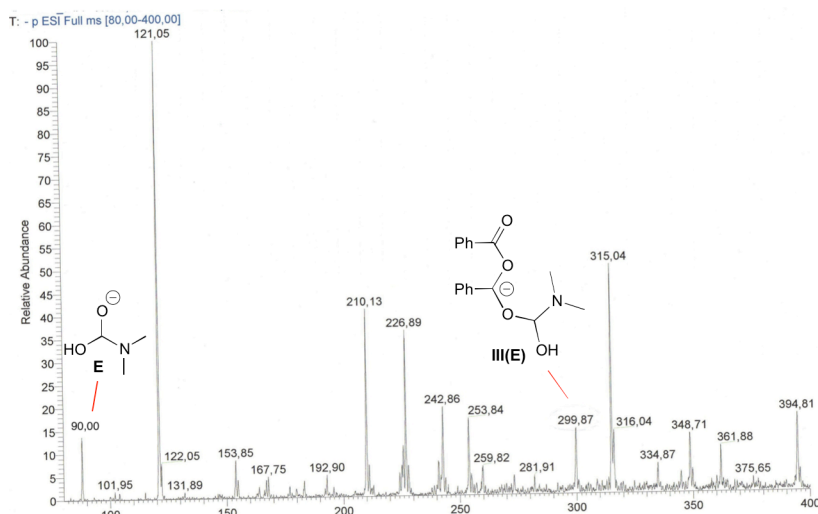


Figure S1. Full scan spectrum of the benzoin-like reaction of **1a** (0.5 M), **2a** (0.5 M) in DMF with $\text{KO}t\text{Bu}$ (0.125 M) showing the presence of anion **E** (m/z 90) and isobaric species **I-III(E)** (m/z 300).

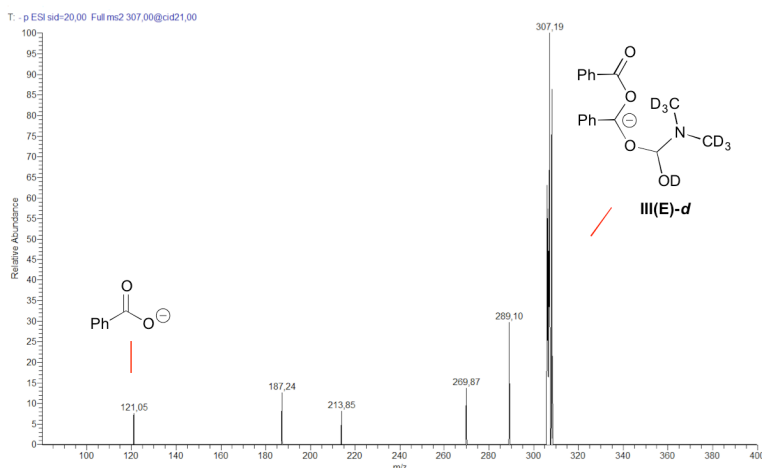


Figure S2. MS/MS mass spectrum of the deuterated adduct **III(E)-d** obtained from $\text{DMF-}d_7$ solutions of **1a** (0.5 M), **2a** (0.5 M) and $\text{KO}t\text{Bu}$ (0.125 M).

EPR experiments

EPR investigation was carried out with a Bruker ER200 MRD spectrometer calibrated with α,α' -diphenylpicrylhydrazyl (dpph, resonance at 3457.41 G, $g = 2.0023$) and equipped with a TE201 resonator (microwave frequency of 9.4 GHz). A flat quartz cell was used for all the experiments. Samples were DMF solutions containing KO t Bu (0.125 M) to which benzyl **1a** (0.5 M) and aldehyde **2a** (0.5 M) were added stepwise and when necessary. In the case of EPR spin trapping experiments, DMF solutions contain from the beginning α -phenyl-N-*tert*-butyl nitron (PBN, 0.5 M) as radical trap. When requested benzyl **1a** (0.5 M) and aldehyde **2a** (0.5 M) were progressively added.

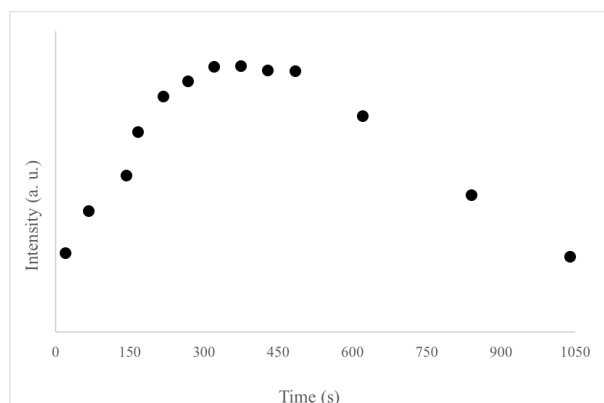


Figure S3. Fixed-field EPR signal intensity of a radical species ($g = 2.0017$) in time obtained by the addition of aldehyde **2a** (0.5 M) to a DMF solution of KO t Bu (0.125 M) and of benzil **1a** (0.5 M).

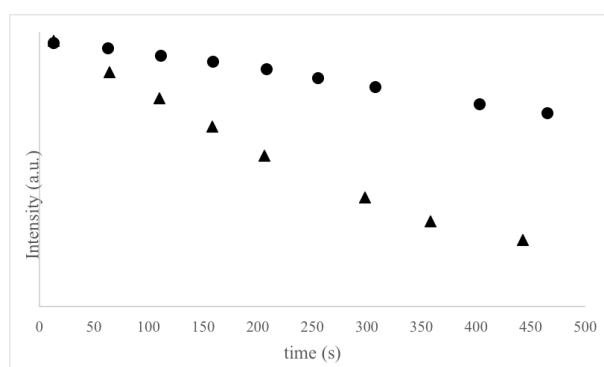


Figure S4. Fixed-field EPR signal intensity of the paramagnetic adduct [PBN-benzil anion radical V] \cdot in time. (●) DMF solution containing KO t Bu (0.125 M), benzil **1a** (0.5 M) and PBN (0.5 M). (▲) the same as before with the addition of aldehyde **2a** (0.5 M).

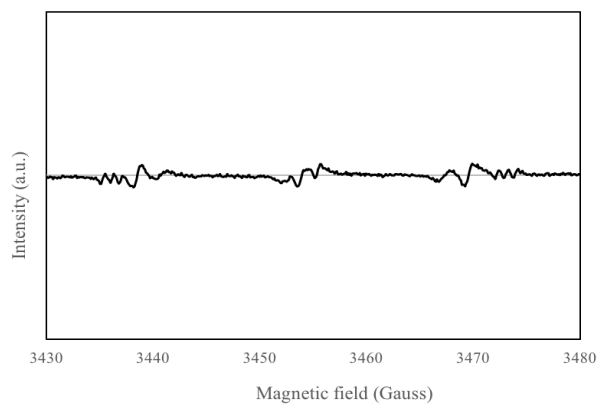


Figure S5. Anaerobic EPR spectrum of a DMF solution containing KO*t*Bu (0.125 M) and PBN (0.5 M).

Computational methods, Cartesian coordinates and energies in Hartree for species calculated

DFT calculations were carried out with the Truhlar M06 hybrid functional,¹ together with the 6-31+G(d,p) basis set within the framework of the Gaussian 09 suite of programs.² All the molecular structures were fully optimized by using the PCM continuum model (N,N-dimethylformamide and dimethylsulfoxide)³ and the Berny analytical gradient optimization method, whereby the stationary points were characterized by frequency calculation. Thermochemical analysis (free energies $\Delta\Delta G$) was performed at 298.15 K, starting from the frequency calculations.

Electronic energies (E, u.a.), Gibbs free energies (ΔG , u.a.), and fully optimized structures [M06//6-31+G(d,p) level using PCM continuum model (N,N-dimethylformamide and dimethylsulfoxide)] are reported in the next pages (pp. S5-S14).

Structures of Figure 3

1a

E = -689.51998

 $\Delta G = -689.36149$

C	-0.868844	-0.494326	0.135532
O	-0.179584	-1.497915	0.254542
C	-1.618674	-0.140331	-1.078274
C	-1.501990	-0.953407	-2.213509
C	-2.225261	-0.652366	-3.357817
C	-3.074060	0.456605	-3.372863
C	-3.199710	1.265450	-2.245241
C	-2.471765	0.970338	-1.098263
H	-0.839556	-1.814750	-2.178466
H	-2.133648	-1.278930	-4.240897
H	-3.641473	0.690780	-4.270210
H	-3.862277	2.126359	-2.260793
H	-2.570196	1.607084	-0.221126
C	-0.862894	0.480119	1.314478
O	-0.162156	1.475682	1.195081
C	-1.616089	0.134804	2.528701
C	-1.489398	0.946476	3.663867
C	-2.215464	0.653801	4.808577
C	-3.077001	-0.445295	4.824097
C	-3.212607	-1.252632	3.696547
C	-2.481938	-0.965940	2.549165
H	-0.817082	1.800112	3.628456
H	-2.116133	1.279264	5.691604
H	-3.646586	-0.672904	5.721758
H	-3.885062	-2.105831	3.712468
H	-2.588200	-1.601503	1.672084

E

E = -324.27277

 $\Delta G = -324.18874$

C	-1.605229	-0.848889	-0.290468
N	-0.643114	0.221028	-0.429466
C	-0.909573	1.279770	0.519908
C	0.764065	-0.252725	-0.407283
O	1.656935	0.680661	-0.576519
H	0.766997	-1.090730	-1.154536
H	-2.611920	-0.490390	-0.545750
H	-1.354575	-1.670419	-0.974704
H	-1.643083	-1.263229	0.736222
H	-1.885681	1.736745	0.308411
H	-0.930214	0.920469	1.568603
H	-0.136215	2.049365	0.433906
O	0.993418	-0.983299	0.872501
H	1.598088	-0.386835	1.333316

TS reactants- I(E)

E = -1013.80292

 $\Delta G = -1013.53566$

C	1.821514	-1.520647	-0.987837
C	1.327215	-1.407429	0.317222
C	2.170695	-1.714647	1.387362
C	3.483801	-2.125374	1.167460
C	3.968057	-2.230668	-0.133088
C	3.132054	-1.926074	-1.209051
C	-0.051995	-0.927358	0.641901
O	-0.358819	-0.642629	1.808998
C	-1.182273	-1.244954	-0.340956
O	-1.020620	-2.119887	-1.181821
C	-2.515299	-0.605025	-0.162852
C	-2.710691	0.629231	0.469286
C	-3.992303	1.157895	0.583810
C	-5.090196	0.460918	0.081272
C	-4.904355	-0.768748	-0.548783
C	-3.623789	-1.293616	-0.673561
O	0.151896	0.928596	-0.468122
C	1.058643	1.652757	0.168104
N	1.444336	2.874280	-0.561333
C	2.457524	3.626272	0.159978
O	0.604906	2.110695	1.467798
C	1.954380	2.516949	-1.873276
H	2.015011	1.078929	0.368821
H	2.753542	4.500779	-0.431442
H	2.071395	3.971580	1.121878
H	3.369520	3.020593	0.349471
H	2.212785	3.426215	-2.428601
H	2.869659	1.889024	-1.807800
H	1.200565	1.959773	-2.434533
H	0.253711	1.309557	1.886904
H	1.784063	-1.619122	2.399392
H	4.127214	-2.359783	2.012477
H	4.993751	-2.545934	-0.311507
H	3.508801	-1.999018	-2.226956
H	1.187340	-1.255149	-1.827329
H	-3.465813	-2.252011	-1.162654
H	-5.757355	-1.316924	-0.941571
H	-6.090269	0.877613	0.178585
H	-4.135237	2.123134	1.064181
H	-1.845847	1.179695	0.823241

IE

E = -1013.81590

 $\Delta G = -1013.54477$

C	1.521792	4.081183	-0.044428
N	0.861926	2.911482	-0.607532
C	1.557555	2.490697	-1.815103

C	0.813878	1.836714	0.356630
O	0.198357	2.298183	1.525667
O	0.105153	0.774397	-0.198065
H	1.853188	1.497104	0.603253
H	1.545783	4.874593	-0.798609
H	0.979831	4.446128	0.830035
H	2.566770	3.862886	0.256011
H	1.563228	3.318670	-2.531682
H	2.610490	2.208380	-1.610492
H	1.052532	1.636103	-2.271166
H	0.034323	1.448370	2.006319
C	0.223777	-0.471875	0.599629
C	-0.930071	-1.379529	0.118707
O	0.020773	-0.295191	1.900553
C	1.581844	-1.078932	0.225808
C	2.472381	-1.474566	1.219015
C	3.718583	-2.009844	0.886941
C	4.080389	-2.161214	-0.448802
C	3.188063	-1.775164	-1.451677
C	1.950021	-1.239467	-1.113059
H	2.173738	-1.348597	2.257634
H	4.407613	-2.308844	1.674651
H	5.050739	-2.577546	-0.711069
H	3.461530	-1.892060	-2.498561
H	1.257402	-0.932081	-1.896349
O	-0.731465	-2.583749	-0.011788
C	-2.324669	-0.847860	-0.020478
C	-3.283400	-1.715683	-0.560633
C	-4.601703	-1.309586	-0.731525
C	-4.985720	-0.024070	-0.353633
C	-4.042862	0.846865	0.189422
C	-2.720524	0.444272	0.351211
H	-2.974857	-2.717913	-0.847709
H	-5.329757	-1.995612	-1.158355
H	-6.016537	0.298381	-0.482576
H	-4.338419	1.850058	0.488210
H	-1.989629	1.130846	0.764077

TS1(E)

E = -1013.79682

 $\Delta G = -1013.52580$

C	-2.512833	-0.622258	-1.191652
C	-1.766997	-1.323425	-0.239840
C	-2.447412	-2.088893	0.712734
C	-3.838978	-2.141330	0.726978
C	-4.574484	-1.436783	-0.224300
C	-3.904901	-0.682770	-1.186912
C	-0.263445	-1.291252	-0.157727
O	0.326551	-2.385228	0.188497
C	0.408142	0.035589	-0.125963
O	0.323981	-0.486361	-1.408817
C	-0.303509	1.331171	0.130197
C	-0.905270	1.574837	1.364692

C	-1.554311	2.784107	1.603252
C	-1.595546	3.760914	0.608924
C	-0.984726	3.524260	-0.622236
C	-0.342658	2.311012	-0.859621
O	1.696794	0.190718	0.435418
C	2.716179	-0.735624	0.119080
O	2.721171	-1.796247	1.004547
N	3.967036	-0.016046	0.203330
C	5.092633	-0.914965	-0.011938
C	3.999773	1.054338	-0.784573
H	-1.991884	-0.035339	-1.943897
H	-4.469472	-0.138797	-1.941584
H	-5.661382	-1.478425	-0.218860
H	-4.350190	-2.736694	1.480741
H	-1.866785	-2.647327	1.443670
H	0.120233	2.107181	-1.824483
H	-1.014972	4.284581	-1.399728
H	-2.104190	4.704671	0.792599
H	-2.030431	2.964053	2.564669
H	-0.875252	0.803370	2.134360
H	2.538372	-1.099946	-0.915440
H	1.825228	-2.210259	0.829044
H	5.043639	-1.409988	-1.003033
H	5.121807	-1.687546	0.758561
H	6.022847	-0.338929	0.032794
H	3.178718	1.756291	-0.617122
H	3.918362	0.663935	-1.819522
H	4.948173	1.594855	-0.699821

II(E)

E = -1013.79632

 $\Delta G = -1013.52900$

C	-2.493403	-1.064633	-1.273116
C	-1.691433	-1.348821	-0.167604
C	-2.304633	-1.753215	1.023032
C	-3.689664	-1.856899	1.112073
C	-4.484325	-1.575847	0.000313
C	-3.880583	-1.185298	-1.192722
C	-0.186921	-1.273851	-0.191336
O	0.437376	-2.356857	0.161233
C	0.431595	0.086699	-0.198520
O	0.301581	-0.517722	-1.449794
C	-0.362665	1.336062	0.034099
C	-0.562604	1.800423	1.336891
C	-1.311599	2.950341	1.567512
C	-1.861896	3.652665	0.494721
C	-1.661346	3.194977	-0.805691
C	-0.918397	2.037731	-1.033523
O	1.731634	0.343102	0.274553
C	2.753974	-0.621760	0.095805
O	2.705468	-1.596854	1.068138
N	4.006614	0.094124	0.179110
C	5.131728	-0.828938	0.115612

C	4.116249	1.072443	-0.894321
H	-1.680571	-1.986911	1.884453
H	-4.150746	-2.162030	2.049272
H	-5.566756	-1.661436	0.065046
H	-4.491932	-0.967666	-2.066290
H	-2.022597	-0.742364	-2.199047
H	-0.774782	1.658309	-2.043253
H	-2.090565	3.736816	-1.645886
H	-2.448546	4.550840	0.674074
H	-1.468480	3.300141	2.585555
H	-0.132407	1.247743	2.171341
H	1.839647	-2.066299	0.850333
H	2.619592	-1.073927	-0.911737
H	5.138050	-1.413087	-0.826946
H	5.105043	-1.527043	0.953879
H	6.063937	-0.256508	0.164336
H	5.073744	1.596172	-0.806125
H	3.310548	1.806896	-0.830505
H	4.077585	0.595656	-1.894657

TS2(E)

E = -1013.76244

 $\Delta G = -1013.49344$

C	2.494728	0.812847	-1.247983
C	1.552964	1.166258	-0.240580
C	1.834329	2.348696	0.496338
C	2.951036	3.126304	0.217332
C	3.854044	2.772728	-0.789641
C	3.606542	1.598992	-1.510948
C	0.352035	0.405454	-0.062635
O	0.399008	-0.953527	-0.397867
C	1.202527	-1.763618	0.425341
O	0.523816	-2.070137	1.633960
O	-0.232054	0.579215	1.261618
C	-1.358340	1.324124	1.107188
C	-2.441624	0.769626	0.253507
C	-2.625320	-0.609836	0.088573
C	-3.723334	-1.086417	-0.618843
C	-4.644154	-0.198538	-1.175647
C	-4.471098	1.174525	-1.005058
C	-3.386207	1.654490	-0.280178
O	-1.487703	2.366850	1.724268
N	1.528283	-2.961752	-0.277393
C	0.373971	-3.776634	-0.629912
C	2.546896	-3.744327	0.400162
H	-1.900890	-1.305774	0.502669
H	-3.860854	-2.158955	-0.737391
H	-5.497197	-0.575878	-1.734709
H	-5.187470	1.872424	-1.432276
H	-3.250514	2.723214	-0.131138
H	1.154024	2.651797	1.289188
H	3.126235	4.026052	0.807081
H	4.726910	3.386060	-1.001071

H	4.299385	1.287659	-2.292553
H	2.324371	-0.094521	-1.825965
H	2.140252	-1.228508	0.661425
H	2.886169	-4.548073	-0.263345
H	3.410172	-3.112910	0.639910
H	2.181183	-4.203954	1.335871
H	0.685192	-4.537581	-1.354626
H	-0.064246	-4.290837	0.242869
H	-0.396950	-3.153213	-1.091618
H	0.187743	-1.231980	1.989493

III(E)

E = -1013.76818

 $\Delta G = -1013.50027$

C	-1.649869	0.768152	-0.746817
O	-1.622223	1.773224	-1.440990
C	-2.916362	0.187135	-0.221758
C	-2.995764	-1.118425	0.274829
C	-4.207610	-1.620029	0.737293
C	-5.349904	-0.820838	0.715945
C	-5.278578	0.479086	0.217675
C	-4.069499	0.977803	-0.254268
H	-2.111712	-1.750345	0.279411
H	-4.261500	-2.638510	1.113964
H	-6.295078	-1.212387	1.084604
H	-6.167398	1.105032	0.197779
H	-4.000994	1.988505	-0.648949
O	-0.577393	0.086634	-0.360978
C	0.737372	0.351785	-0.946632
O	1.382020	-0.895626	-1.042165
C	1.462018	1.400793	-0.289111
C	0.841575	2.442205	0.450873
C	1.577406	3.500364	0.973538
C	2.960990	3.578877	0.805396
C	3.596617	2.548960	0.099212
C	2.876837	1.490602	-0.430032
H	-0.234229	2.420339	0.605626
H	1.055991	4.277791	1.531822
H	3.529428	4.410243	1.215835
H	4.677587	2.572954	-0.036788
H	3.396882	0.703547	-0.974946
C	1.784296	-1.495049	0.166883
N	2.823177	-2.435653	-0.099932
H	2.180162	-0.720452	0.845484
O	0.685175	-2.137737	0.795617
C	3.470815	-2.904318	1.112333
C	2.423799	-3.543463	-0.955338
H	4.370587	-3.470823	0.846041
H	3.775878	-2.051155	1.729210
H	2.820675	-3.559104	1.720040
H	3.320584	-4.088145	-1.271952
H	1.753065	-4.254480	-0.442489
H	1.917273	-3.163855	-1.846417
H	-0.014915	-1.473385	0.879251

Structures of Figure 6

IX

E = -689.720593

 $\Delta G = -689.56415$

C	-0.868841	-0.494330	0.135534
O	-0.179583	-1.497910	0.254564
C	-1.618643	-0.140329	-1.078296
C	-1.501947	-0.953410	-2.213531
C	-2.225244	-0.652381	-3.357827
C	-3.074088	0.456562	-3.372850
C	-3.199733	1.265415	-2.245239
C	-2.471737	0.970330	-1.098275
H	-0.839493	-1.814736	-2.178485
H	-2.133620	-1.278935	-4.240912
H	-3.641544	0.690707	-4.270178
H	-3.862281	2.126336	-2.260787
H	-2.570125	1.607110	-0.221157
C	-0.862945	0.480164	1.314466
O	-0.162210	1.475727	1.195047
C	-1.616113	0.134843	2.528703
C	-1.489387	0.946471	3.663900
C	-2.215432	0.653764	4.808613
C	-3.076995	-0.445312	4.824109
C	-3.212637	-1.252605	3.696535
C	-2.481980	-0.965885	2.549149
H	-0.817034	1.800079	3.628517
H	-2.116058	1.279176	5.691670
H	-3.646588	-0.672923	5.721765
H	-3.885111	-2.105789	3.712428
H	-2.588277	-1.601397	1.672031

2g

E = -345.35472

 $\Delta G = -345.27556$

C	0.268305	2.014169	0.000000
O	1.378007	2.519124	0.000000
H	-0.641292	2.654029	0.000000
C	0.000000	0.571178	0.000000
C	-1.326963	0.130471	0.000000
C	-1.608624	-1.231679	0.000000
C	-0.561444	-2.151406	0.000000
C	0.766275	-1.715410	0.000000
C	1.048926	-0.357074	0.000000
H	-2.133888	0.862274	0.000000
H	-2.639057	-1.576747	0.000000
H	-0.779298	-3.216686	0.000000
H	1.575657	-2.440839	0.000000

H 2.074963 0.003485 0.000000

TS IX-2g

E = -1035.07880

 $\Delta G = -1034.81931$

C	-1.373562	2.016923	-0.599740
C	-1.014153	1.217668	0.500727
C	-1.943186	1.118646	1.547395
C	-3.165804	1.787335	1.512587
C	-3.501224	2.583029	0.417755
C	-2.593667	2.687096	-0.639082
C	0.245319	0.390473	0.587909
O	0.379115	-0.315110	1.710711
C	1.481740	1.090511	0.109751
C	2.807352	0.371231	0.159028
C	3.813425	0.837095	-0.702062
C	5.066002	0.235878	-0.742134
C	5.347227	-0.845460	0.094111
C	4.360607	-1.318985	0.955387
C	3.099384	-0.723309	0.986148
O	1.484507	2.224217	-0.392723
H	3.587308	1.682046	-1.348588
H	5.825139	0.608909	-1.427035
H	6.329035	-1.314464	0.071713
H	4.572608	-2.161861	1.610953
H	2.305944	-1.070532	1.642571
H	-1.673244	0.482385	2.387773
H	-3.860936	1.687498	2.346098
H	-4.451869	3.112903	0.386152
H	-2.842773	3.295834	-1.508230
H	-0.694223	2.080175	-1.442633
C	0.109835	-0.774120	-0.896751
O	0.295814	-0.244398	-2.083370
H	0.918227	-1.438780	-0.502663
C	-1.212235	-1.439388	-0.648387
C	-1.373634	-2.402177	0.357357
C	-2.618587	-2.972278	0.619015
C	-3.733883	-2.605286	-0.135171
C	-3.582498	-1.667721	-1.159678
C	-2.337033	-1.099643	-1.413413
H	-0.503204	-2.688597	0.943411
H	-2.718885	-3.716660	1.408222
H	-4.705656	-3.054627	0.062048
H	-4.442549	-1.382529	-1.765076
H	-2.208961	-0.364473	-2.206179

X

E = -1035.08485

 $\Delta G = -1013.82566$

C	2.303724	1.216051	-1.318569
C	1.253334	1.507293	-0.441406
C	1.488734	2.455525	0.562075
C	2.736318	3.061354	0.711110
C	3.779989	2.740829	-0.157186
C	3.553127	1.817443	-1.179561
C	-0.089732	0.800764	-0.570382
O	-0.368410	0.334459	-1.811115
C	-0.193268	-0.346871	0.546451
C	-1.502770	-1.102323	0.307175
O	-1.590331	-2.332624	0.365297
C	1.011402	-1.271120	0.374325
C	1.244327	-2.008969	-0.794972
C	2.404553	-2.763948	-0.951032
C	3.365182	-2.804735	0.061638
C	3.140868	-2.086556	1.234885
C	1.973112	-1.336775	1.384916
O	-0.370963	0.090793	1.828838
C	-2.786662	-0.330520	0.160847
C	-3.765680	-0.868392	-0.683755
C	-4.983216	-0.221348	-0.873384
C	-5.250771	0.970036	-0.199545
C	-4.290423	1.504858	0.657532
C	-3.065211	0.864798	0.834013
H	-3.554403	-1.800594	-1.204417
H	-5.724815	-0.647084	-1.546317
H	-6.204899	1.474681	-0.337654
H	-4.498866	2.426417	1.198168
H	-2.304738	1.249474	1.508566
H	1.781582	-0.772132	2.296019
H	3.876125	-2.112912	2.038473
H	4.271021	-3.396166	-0.060481
H	2.562926	-3.326216	-1.870882
H	0.513855	-1.949773	-1.597171
H	-0.834119	1.548306	-0.190406
H	0.674257	2.711567	1.239092
H	2.893032	3.793742	1.502131
H	4.754140	3.214095	-0.047235
H	4.355820	1.568639	-1.873125
H	2.115087	0.492564	-2.109964

TS X-XI

E = -1035.07345

 $\Delta G = -1034.81165$

C	-3.129480	0.499457	1.023593
C	-2.759025	-0.282798	-0.076843
C	-3.724062	-0.519869	-1.065886
C	-5.004074	0.016238	-0.976948
C	-5.361245	0.797312	0.124532
C	-4.418640	1.030070	1.122095
C	-1.380367	-0.913345	-0.288743
O	-1.407033	-2.060578	-0.828936

C	-0.225832	-0.472496	0.710539
O	-0.526953	-0.400232	2.015942
C	-0.118892	0.880865	-0.125837
O	-0.693851	0.386892	-1.295902
C	1.212987	1.540590	-0.261260
C	2.033145	1.362836	-1.380942
C	3.302235	1.935710	-1.440047
C	3.782563	2.700399	-0.376401
C	2.969739	2.898544	0.740424
C	1.697820	2.333442	0.789162
C	1.055785	-1.288729	0.442623
C	1.467705	-1.751924	-0.816537
C	2.682696	-2.413317	-0.985125
C	3.532838	-2.627935	0.100464
C	3.139757	-2.178138	1.359126
C	1.915279	-1.527635	1.519379
H	-3.446354	-1.139331	-1.917070
H	-5.729555	-0.175608	-1.766361
H	-6.363892	1.213731	0.203610
H	-4.687470	1.627856	1.992406
H	-2.385292	0.652298	1.803354
H	1.588470	-1.181373	2.498356
H	3.785806	-2.337641	2.221928
H	4.483652	-3.141174	-0.033743
H	2.971440	-2.761942	-1.976505
H	0.823470	-1.577570	-1.671684
H	-0.782334	1.594960	0.412731
H	1.060062	2.506508	1.657068
H	3.324901	3.504812	1.572119
H	4.773821	3.146777	-0.422491
H	3.921945	1.784841	-2.322723
H	1.658421	0.758532	-2.204041

XI

E = -1035.07839

 $\Delta G = -1034.81772$

C	3.234946	-1.226172	-0.463869
C	2.749166	0.068494	-0.274601
C	3.621635	1.017937	0.274345
C	4.927775	0.687357	0.619896
C	5.403917	-0.610077	0.411486
C	4.550647	-1.564035	-0.134595
C	1.351486	0.524548	-0.714200
O	1.414409	1.518730	-1.553706
O	0.630445	-0.729824	-1.269131
C	0.039100	-0.997726	-0.015802
C	0.317091	0.477228	0.535390
C	-0.938234	1.323846	0.280667
C	-1.342764	-1.539532	-0.043793
C	-1.889748	-2.050639	1.142234
C	-3.213586	-2.474791	1.199261
C	-4.017452	-2.418557	0.059704
C	-3.477530	-1.933457	-1.131557

C	-2.155887	-1.494462	-1.181056
O	0.783452	0.586777	1.781808
H	0.671263	-1.660827	0.610571
H	-1.737726	-1.099222	-2.104008
H	-4.092808	-1.894074	-2.029037
H	-5.050711	-2.757010	0.098194
H	-3.619021	-2.859013	2.133756
H	-1.261758	-2.101626	2.032688
H	3.261889	2.034882	0.424671
H	5.583567	1.443693	1.048981
H	6.428565	-0.869052	0.671672
H	4.907891	-2.578318	-0.308329
H	2.567364	-1.972016	-0.891056
C	-1.732623	1.660798	1.383344
C	-2.941586	2.340563	1.241624
C	-3.382273	2.726718	-0.024069
C	-2.596693	2.415778	-1.133714
C	-1.398815	1.716351	-0.985195
H	-1.367834	1.369075	2.366782
H	-3.538795	2.574973	2.122357
H	-4.320776	3.265654	-0.143323
H	-2.922894	2.717429	-2.128891
H	-0.786092	1.478968	-1.849790

C	4.192712	0.196918	-0.625152
C	5.237084	-0.476930	-0.025891
C	5.013308	-1.624276	0.766530
C	3.683537	-2.068724	0.931722
C	2.622644	-1.410456	0.341563
H	4.384289	1.081047	-1.231226
H	6.255112	-0.112945	-0.169212
H	5.841431	-2.150617	1.236215
H	3.484509	-2.953237	1.537888
H	1.608006	-1.780067	0.480930
C	-1.702965	2.787777	-0.261151
C	-1.956766	3.723499	0.73662
C	-1.317954	3.620635	1.973677
C	-0.423728	2.575988	2.194440
C	-0.172696	1.637245	1.193662
H	-2.200121	2.872622	-1.227414
H	-2.651250	4.539887	0.548027
H	-1.510558	4.353588	2.754054
H	0.087119	2.490328	3.151754
H	0.537981	0.830845	1.368711

3ag

E = -1035.07860

 $\Delta G = -1034.82244$

C	1.783794	0.476576	-1.095854
O	0.531324	-0.107788	-0.901044
C	2.833259	-0.239188	-0.464833
C	-0.600803	0.715899	-1.152777
C	-1.857521	-0.119921	-1.403326
C	-0.815273	1.726743	-0.044554
H	-0.439389	1.271166	-2.086357
O	-2.562797	0.229795	-2.416952
C	-2.268742	-1.160389	-0.509269
C	-1.546020	-1.568935	0.656454
C	-2.014726	-2.575075	1.482849
C	-3.219242	-3.247941	1.209687
C	-3.941063	-2.871784	0.065627
C	-3.488125	-1.864657	-0.768549
H	-0.599549	-1.088920	0.889881
H	-1.430544	-2.851043	2.361130
H	-3.578349	-4.039336	1.864204
H	-4.876666	-3.379089	-0.171895
H	-4.062718	-1.583890	-1.648680
O	1.894773	1.515697	-1.790361

Structures of Figure 7

1a

E = -689.52009
 $\Delta G = -689.36163$

C	-0.869134	-0.494387	0.135581
O	-0.178820	-1.497332	0.254307
C	-1.618840	-0.140468	-1.078278
C	-1.501431	-0.953149	-2.213748
C	-2.224561	-0.652129	-3.358148
C	-3.073952	0.456405	-3.373052
C	-3.200343	1.264835	-2.245204
C	-2.472546	0.969758	-1.098126
H	-0.838599	-1.814192	-2.178853
H	-2.132421	-1.278383	-4.241388
H	-3.641289	0.690533	-4.270453
H	-3.863429	2.125341	-2.260632
H	-2.571684	1.606113	-0.220787
C	-0.863178	0.480174	1.314430
O	-0.161403	1.475086	1.195310
C	-1.616251	0.134938	2.528705
C	-1.488841	0.946211	3.664103
C	-2.214769	0.653563	4.808904
C	-3.076894	-0.445089	4.824285
C	-3.213232	-1.252009	3.696514
C	-2.482708	-0.965357	2.549033
H	-0.816132	1.799544	3.628837
H	-2.114918	1.278714	5.692088
H	-3.646402	-0.672649	5.722001
H	-3.886200	-2.104801	3.712314
H	-2.589670	-1.600527	1.671753

A

E = -552.55401
 $\Delta G = -552.51673$

S	-0.116880	0.155787	-0.414269
O	0.153199	1.497517	0.355873
C	1.306603	-0.836120	0.126744
C	-1.379005	-0.831504	0.192787
H	1.320864	-1.793470	-0.399757
H	2.220072	-0.272396	-0.082114
H	1.209585	-0.998461	1.207457
H	-2.346180	-0.443998	-0.146471
H	-1.325445	-0.958661	1.285016

TS reactants- I(A)

E = -1242.08945
 $\Delta G = -1242.86994$

C	2.644689	-0.647187	1.413212
C	1.794993	-0.918882	0.332925
C	2.367569	-1.428634	-0.842519
C	3.740083	-1.653789	-0.924062
C	4.571775	-1.373864	0.158191
C	4.016091	-0.865726	1.330599
C	0.322696	-0.649020	0.560537
O	-0.032105	-0.293977	1.704732
C	-0.688136	-1.056588	-0.464783
O	-0.430573	-1.798205	-1.434276
C	-2.139565	-0.788905	-0.145262
C	-3.053981	-1.770931	-0.540634
C	-4.415342	-1.634402	-0.277942
C	-4.884951	-0.499991	0.378501
C	-3.983132	0.491444	0.766077
C	-2.621969	0.349753	0.512766
C	0.112421	0.952797	-0.991629
S	0.729345	2.323520	-0.033139
C	1.168002	3.462675	-1.384834
O	-0.480674	2.984718	0.638416
H	2.199400	-0.255891	2.324560
H	4.651629	-0.639581	2.184323
H	5.642917	-1.550297	0.088138
H	4.161323	-2.052189	-1.844968
H	1.728688	-1.657067	-1.688543
H	-2.680270	-2.651399	-1.058205
H	-5.107735	-2.414081	-0.588501
H	-5.947354	-0.384279	0.582490
H	-4.344554	1.386570	1.268488
H	-1.932847	1.137777	0.807681
H	0.873773	0.645531	-1.716114
H	-0.826885	1.255372	-1.473480
H	1.518612	4.397156	-0.936365
H	1.962122	3.014774	-1.989370
H	0.271013	3.638495	-1.987745

I(A)

E = -1242.12891
 $\Delta G = -1242.90585$

C	0.615146	-1.685936	1.316199
C	0.185170	-1.468723	0.003472
C	0.482167	-2.425119	-0.965791
C	1.196475	-3.575533	-0.634699
C	1.628347	-3.781022	0.674742
C	1.336109	-2.829367	1.651893
C	-0.631713	-0.222743	-0.375554
O	-0.712369	0.048520	-1.699873

C	-0.022443	1.042699	0.253039
O	-0.715892	1.814635	0.916345
C	1.407096	1.383596	-0.018653
C	2.155125	0.796541	-1.047829
C	3.496318	1.125174	-1.214047
C	4.110819	2.032711	-0.350943
C	3.375328	2.618838	0.677376
C	2.031215	2.298203	0.838218
C	-2.026399	-0.456929	0.243863
S	-3.210737	0.825724	-0.326513
O	-4.253739	0.090731	-1.178328
C	-4.030441	1.085728	1.273172
H	0.155490	-2.235080	-1.987022
H	1.421994	-4.313151	-1.402772
H	2.193004	-4.674330	0.932742
H	1.673107	-2.977594	2.675908
H	0.395180	-0.945446	2.088062
H	1.448814	2.747549	1.639229
H	3.849829	3.324308	1.355567
H	5.161381	2.282788	-0.481196
H	4.065909	0.673015	-2.022811
H	1.655975	0.109392	-1.726274
H	-2.442355	-1.388701	-0.160837
H	-2.025675	-0.499144	1.339827
H	-4.855601	1.783120	1.109022
H	-4.413192	0.127899	1.641015
H	-3.305978	1.513985	1.971862

TS1(A)

E = -1242.11413

 $\Delta G = -1242.89217$

C	-0.561823	1.514487	1.229301
C	-0.285027	1.393466	-0.135585
C	-0.877561	2.283366	-1.029040
C	-1.734224	3.282392	-0.567858
C	-2.013589	3.392521	0.792841
C	-1.425587	2.502285	1.692916
C	0.656397	0.320222	-0.624825
C	2.087436	0.750189	-0.333207
S	3.415089	-0.506904	-0.134205
C	3.057120	-0.934332	1.595355
C	0.272439	-1.115378	-0.523930
C	-1.184002	-1.423716	-0.311101
C	-2.223000	-0.965519	-1.124820
C	-3.548187	-1.264948	-0.815111
C	-3.855605	-2.017099	0.317916
C	-2.824963	-2.480060	1.133938
C	-1.500472	-2.191175	0.814954
O	1.118665	-2.043667	-0.383151
O	0.436508	-0.139438	-1.927755
O	4.664337	0.382934	-0.027143
H	-0.691572	-2.554117	1.447488
H	-3.052862	-3.069151	2.019928

H	-4.891373	-2.244015	0.560952
H	-4.346184	-0.908318	-1.463366
H	-1.977288	-0.373000	-2.002300
H	-0.675170	2.170123	-2.092914
H	-2.190146	3.973471	-1.274031
H	-2.689280	4.165393	1.152287
H	-1.643614	2.578017	2.756074
H	-0.103940	0.813042	1.929991
H	2.441135	1.347530	-1.185356
H	2.168516	1.373503	0.567825
H	3.804486	-1.664937	1.914960
H	3.159402	-0.014508	2.181292
H	2.054257	-1.361398	1.668367

IIA

E = -1242.11658

 $\Delta G = -1242.89346$

C	0.250752	-1.130025	-0.597927
C	-1.179910	-1.412031	-0.209817
C	-1.449430	-1.765616	1.115762
C	-2.743921	-2.073502	1.522659
C	-3.790660	-2.046761	0.599769
C	-3.529821	-1.701177	-0.724335
C	-2.232881	-1.377859	-1.123741
H	-0.627896	-1.795785	1.831638
H	-2.938929	-2.337015	2.560318
H	-4.802972	-2.292848	0.912843
H	-4.340450	-1.678207	-1.450110
H	-2.027995	-1.088971	-2.152498
O	1.102917	-2.080451	-0.415757
C	0.666251	0.332332	-0.630175
O	0.337032	-0.328362	-1.848655
C	-0.257847	1.437466	-0.228936
C	-1.162999	1.986695	-1.138900
C	-2.021483	3.015263	-0.753634
C	-1.994241	3.502831	0.550906
C	-1.099640	2.953674	1.470043
C	-0.239077	1.931971	1.081368
H	-1.192720	1.591441	-2.151929
H	-2.717453	3.435761	-1.476788
H	-2.666544	4.302770	0.852433
H	-1.075153	3.319901	2.494132
H	0.451396	1.502330	1.808680
C	2.123395	0.706271	-0.508842
H	2.295494	1.474378	0.256527
H	2.478287	1.111874	-1.466760
S	3.393192	-0.571899	-0.116366
O	4.655066	0.302283	-0.013655
C	2.922068	-0.838350	1.616053
H	3.633984	-1.550296	2.041374
H	3.007324	0.125636	2.129638
H	1.909101	-1.245421	1.655377

TS2(A)

E = -1242.09899

 $\Delta G = -1242.87697$

C	1.369350	2.012493	0.930659
C	0.128337	1.629239	0.365823
C	-0.361115	2.454163	-0.678466
C	0.345983	3.559466	-1.131181
C	1.577423	3.906901	-0.570104
C	2.071579	3.120957	0.470954
C	-0.605704	0.487481	0.852943
C	-2.084082	0.456151	0.830288
S	-2.928516	-0.803342	-0.289288
C	-2.328477	-0.168042	-1.874071
O	-0.018974	-0.164377	1.996219
C	-0.016592	-1.331540	1.262107
O	-0.847302	-2.218374	1.494011
C	1.161000	-1.584918	0.390149
C	2.432143	-1.082415	0.684010
C	3.521286	-1.402183	-0.125639
C	3.354536	-2.225562	-1.235627
C	2.090404	-2.745401	-1.524805
C	1.007800	-2.438593	-0.710949
O	-4.407930	-0.399949	-0.232925
H	0.021081	-2.847139	-0.922687
H	1.952960	-3.395245	-2.386258
H	4.204430	-2.469900	-1.868674
H	4.505881	-1.008960	0.118286
H	2.572401	-0.457810	1.560957
H	1.762025	1.439854	1.765295
H	3.018573	3.378727	0.943535
H	2.131132	4.770560	-0.930582
H	-0.072762	4.159335	-1.937880
H	-1.314035	2.223471	-1.148294
H	-2.545721	1.399342	0.500075
H	-2.506090	0.190955	1.808165
H	-2.693153	-0.836989	-2.657430
H	-2.736938	0.838522	-2.021383
H	-1.233091	-0.158808	-1.869513

III(A)

E = -1242.11389

 $\Delta G = -1242.89445$

C	3.926028	0.170508	0.945040
C	2.744429	-0.132678	0.261216
C	2.815243	-0.733918	-1.001352
C	4.052038	-1.026564	-1.566366
C	5.226591	-0.718456	-0.880934
C	5.161244	-0.118778	0.376240
C	1.448622	0.178641	0.919388

O	1.363121	0.663620	2.039295
O	0.410714	-0.122681	0.145416
C	-0.930622	0.071271	0.595787
C	-1.296821	1.440910	0.881390
S	-1.363978	2.597347	-0.671859
O	-1.687801	4.012646	-0.160471
C	-1.779925	-1.023548	0.326351
C	-1.278041	-2.273273	-0.154871
C	-2.110941	-3.362169	-0.368628
C	-3.486388	-3.296588	-0.123295
C	-4.002652	-2.081261	0.346311
C	-3.191091	-0.979531	0.559004
C	-2.920352	1.962315	-1.343486
H	-0.211621	-2.370789	-0.349439
H	-1.672543	-4.290467	-0.736046
H	-4.131815	-4.155257	-0.291835
H	-5.069931	-1.989709	0.548603
H	-3.645565	-0.059582	0.925354
H	1.898862	-0.970994	-1.535200
H	4.100759	-1.494939	-2.546425
H	6.192296	-0.944478	-1.326939
H	6.074909	0.123617	0.913576
H	3.859206	0.635152	1.925555
H	-2.293104	1.551440	1.327004
H	-0.569334	1.993007	1.490363
H	-3.123992	2.473454	-2.287734
H	-2.818354	0.884784	-1.511118
H	-3.718565	2.167248	-0.620656

Other Structures**DMF**

E = -248.37578

 $\Delta G = -248.303206$

C	-0.088010	0.178702	0.076812
O	-0.086063	0.018952	1.295257
H	0.645549	0.834461	-0.429528
N	-0.943573	-0.393269	-0.792522
C	-0.863202	-0.140987	-2.216512
C	-1.988168	-1.292837	-0.346679
H	-1.797938	0.303010	-2.579844
H	-0.041294	0.548488	-2.427092
H	-0.687140	-1.076404	-2.761429
H	-2.972151	-0.897994	-0.627153
H	-1.862917	-2.277479	-0.813081
H	-1.935625	-1.396828	0.738180

C (Scheme 1)

E = -247.83143
 DG = -247.77322

C	0.020165	0.072202	-0.068182
N	0.116198	0.348413	1.338567
C	1.420347	0.120210	1.924323
C	-1.006929	0.805351	2.052647
O	-0.809993	1.015696	3.282488
H	0.256232	-0.980385	-0.297585
H	-1.006432	0.280059	-0.393927
H	0.710442	0.698054	-0.658206
H	1.735264	-0.929292	1.811656
H	2.190795	0.749781	1.451685
H	1.362098	0.364484	2.989994

F (Scheme 5)

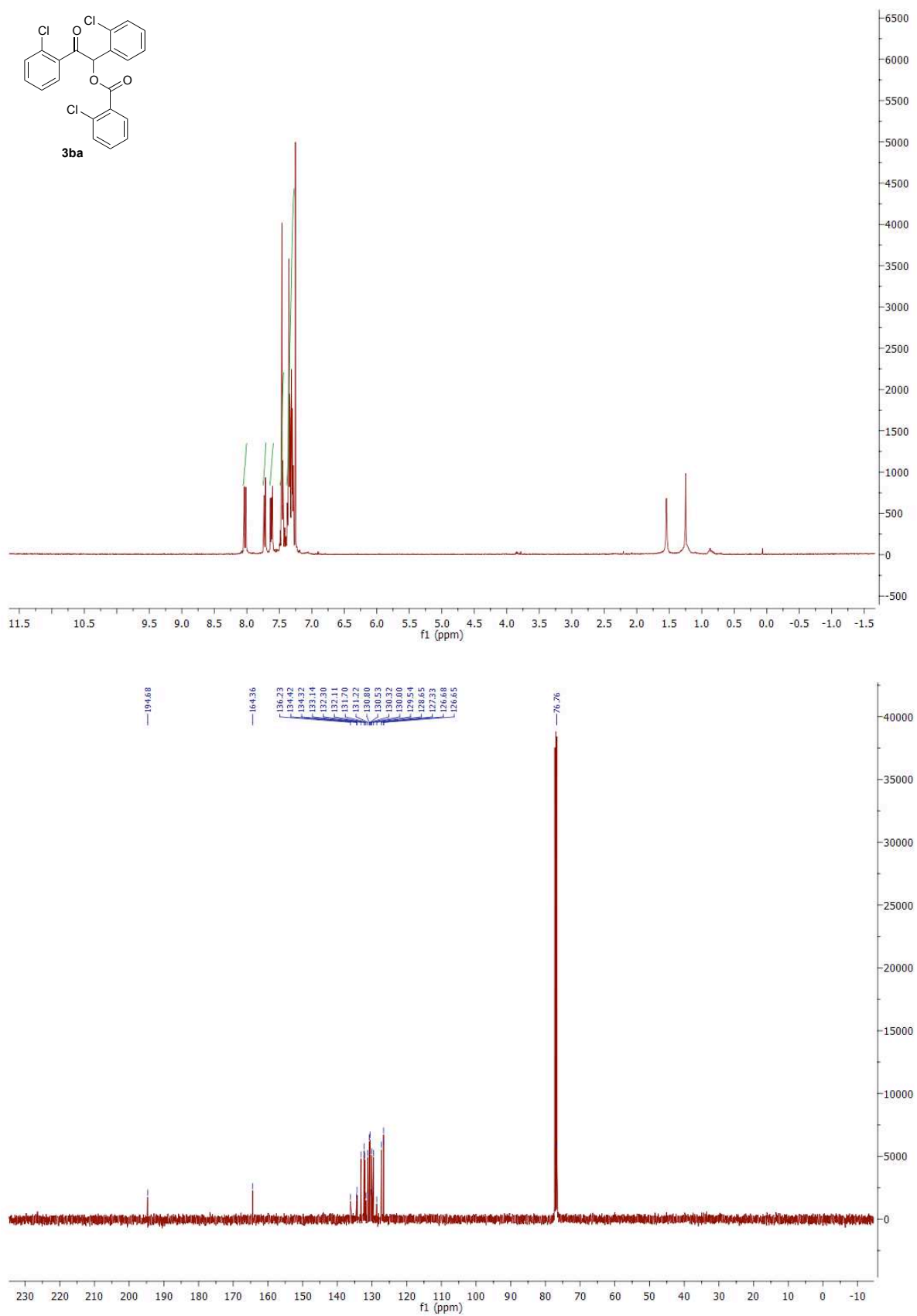
E = -247.71468
 DG = -247.65524

247.714678			
C	-0.000105	0.079460	-0.077170
N	0.139157	0.343197	1.344975
C	1.456573	0.109132	1.935481
C	-0.886069	0.776118	2.064813
O	-0.976853	1.050810	3.240578
H	0.228418	-0.971222	-0.290270
H	-1.026076	0.295015	-0.383540
H	0.688932	0.712877	-0.647802
H	1.741332	-0.940616	1.802422
H	2.201685	0.744469	1.443672
H	1.421192	0.345334	3.000300

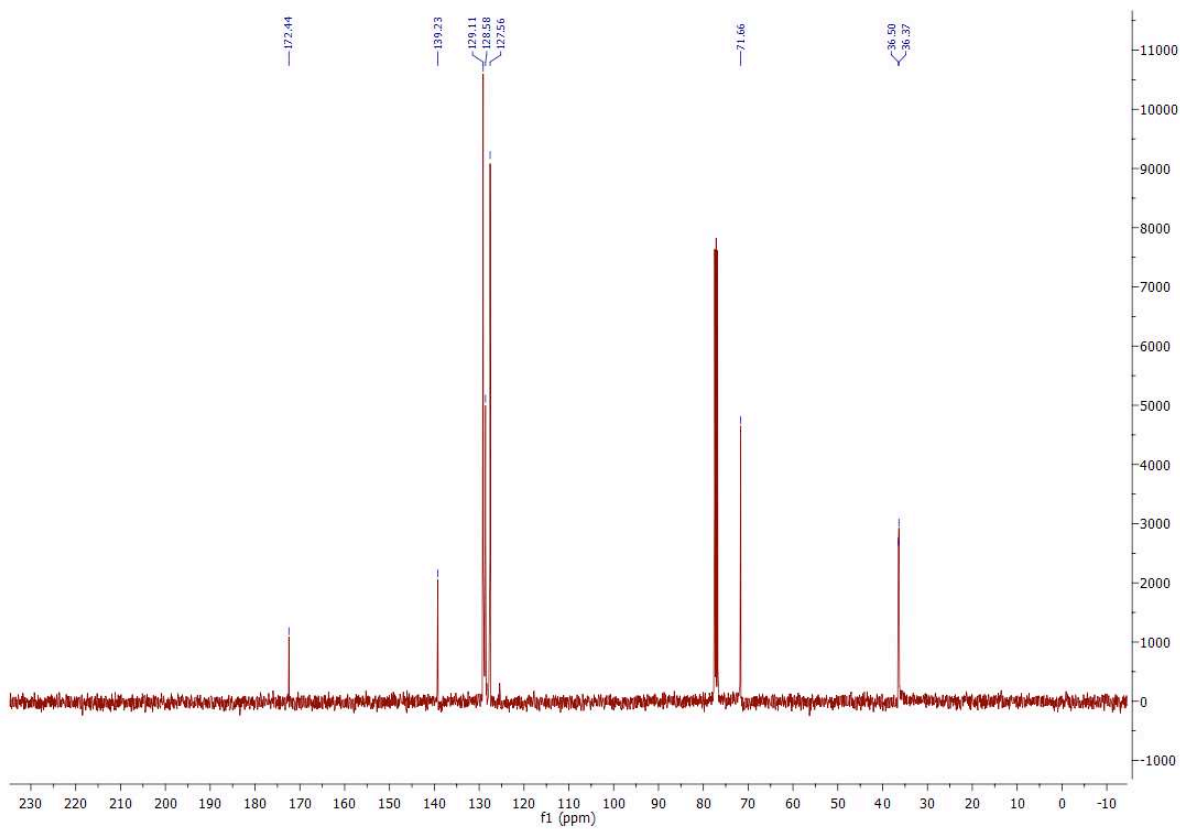
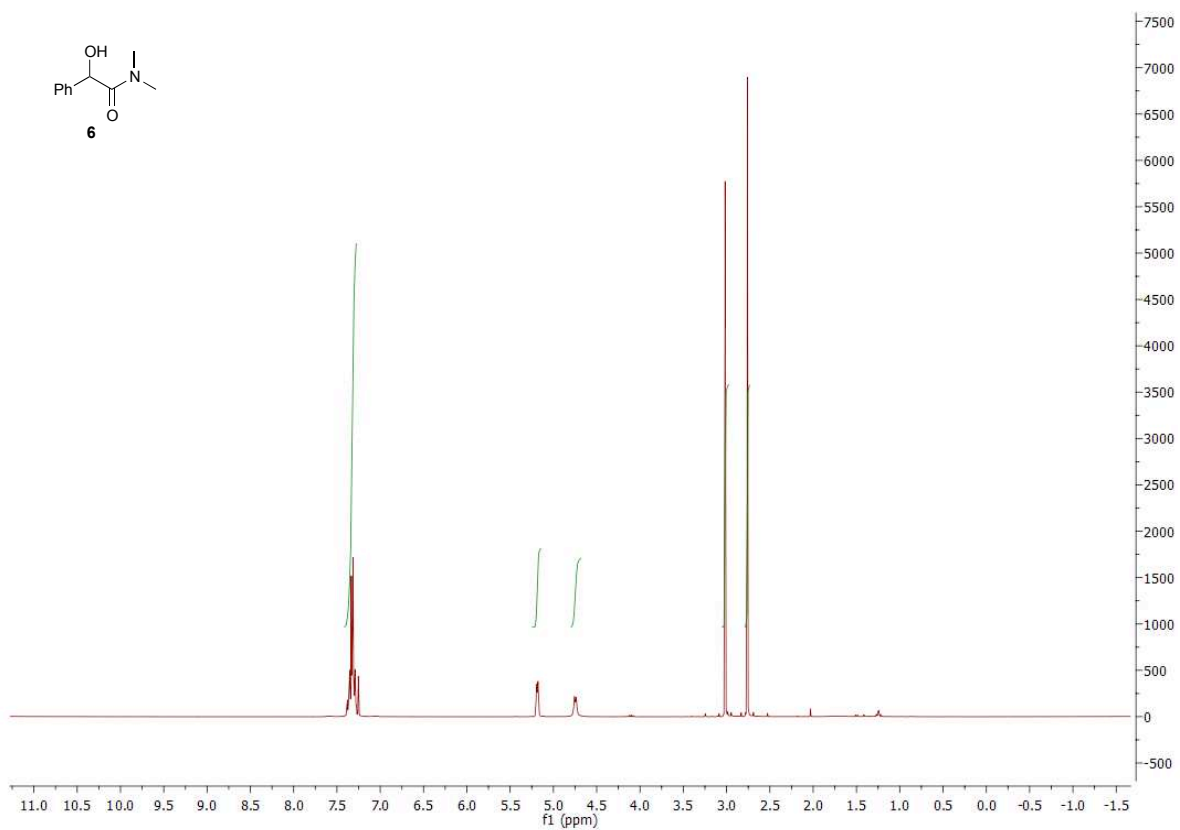
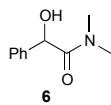
V (Scheme 5)

E = -689.63884
 DG = -689.48333

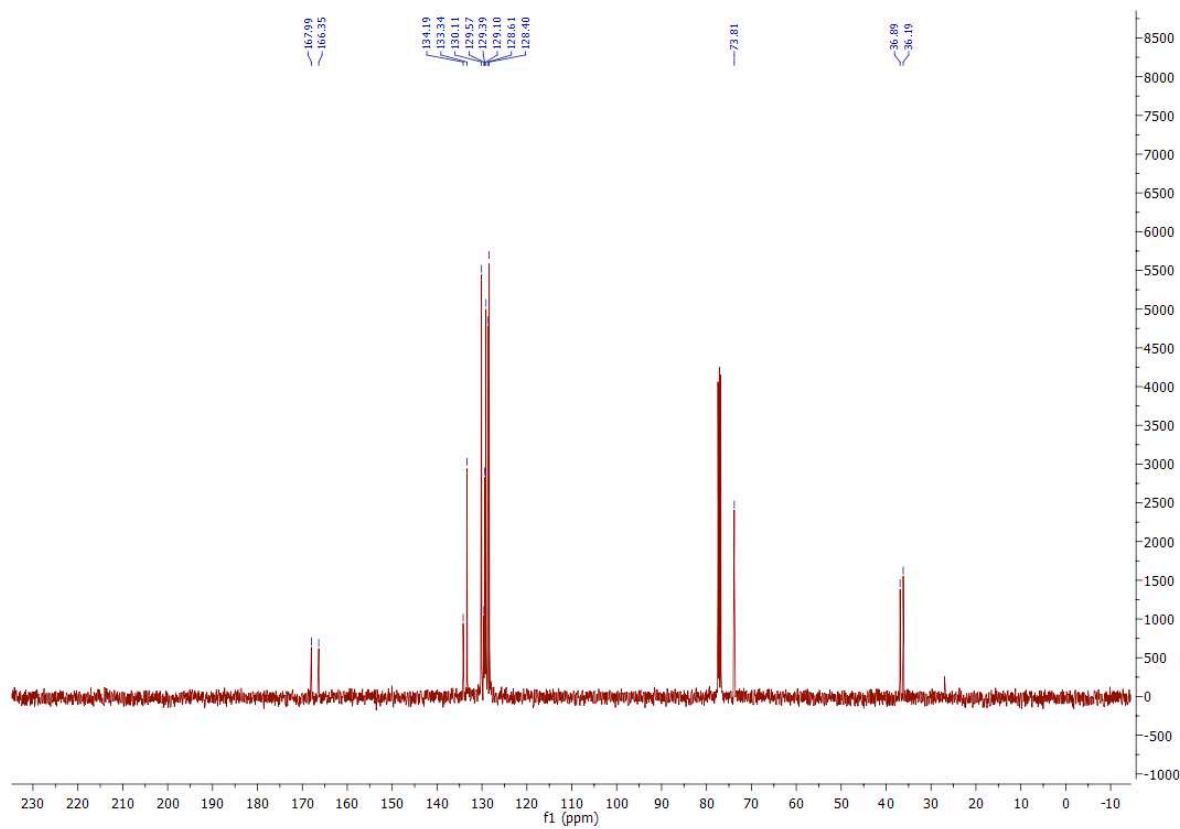
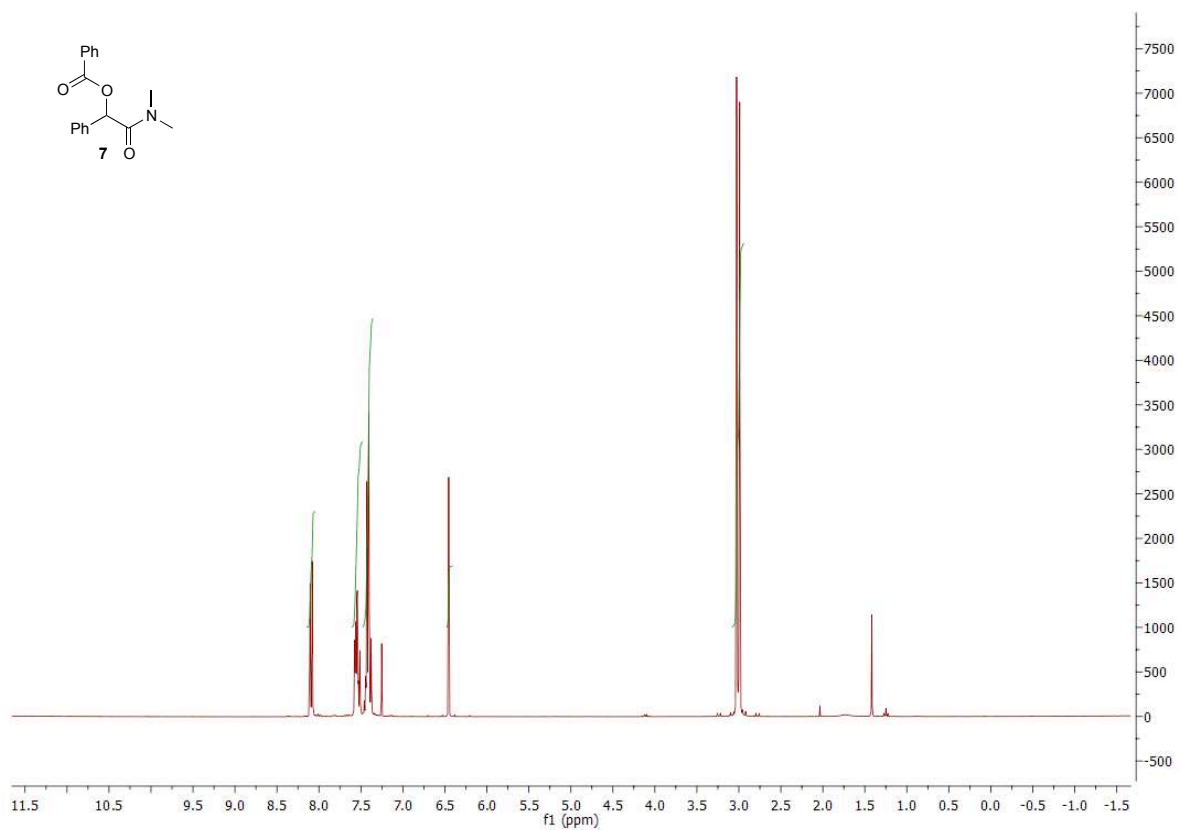
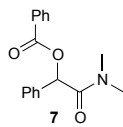
C	-1.937592	-0.477647	0.173333
O	-1.812954	-1.725659	0.364292
C	-2.056161	0.002122	-1.235804
C	-1.718255	-0.903956	-2.256781
C	-1.845261	-0.566659	-3.599303
C	-2.331249	0.689209	-3.963280
C	-2.685489	1.596024	-2.964648
C	-2.545950	1.263842	-1.619818
H	-1.353347	-1.886503	-1.966991
H	-1.566221	-1.287015	-4.366140
H	-2.435107	0.956761	-5.012686
H	-3.075239	2.575631	-3.235759
H	-2.814318	1.981640	-0.851438
C	-1.931763	0.475771	1.277266
O	-1.792794	1.722257	1.086230
C	-2.055095	-0.002595	2.686472
C	-1.706194	0.899525	3.707255
C	-1.836351	0.563721	5.049850
C	-2.336604	-0.686453	5.414105
C	-2.701833	-1.589121	4.415674
C	-2.559205	-1.258576	3.070765
H	-1.330126	1.877793	3.417256
H	-1.548596	1.280810	5.816527
H	-2.442969	-0.952784	6.463569
H	-3.102715	-2.564164	4.687007
H	-2.836260	-1.973231	2.302538

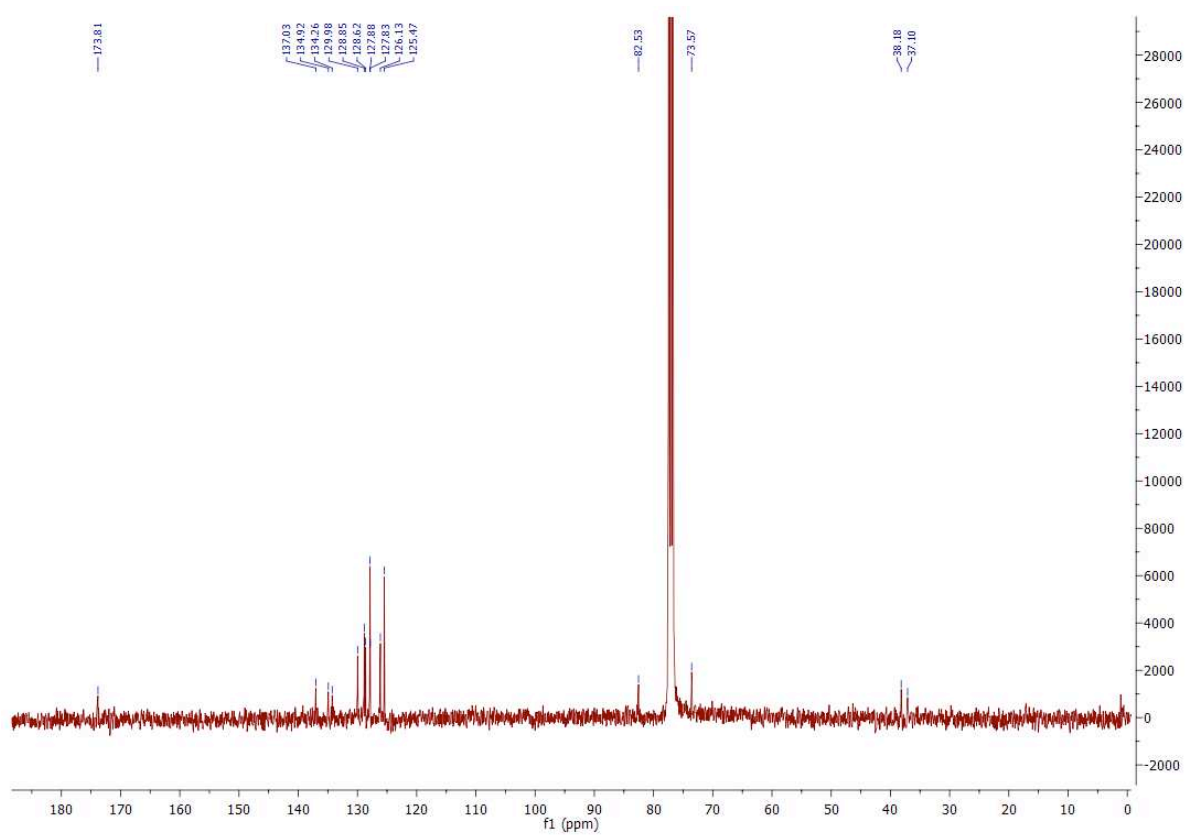
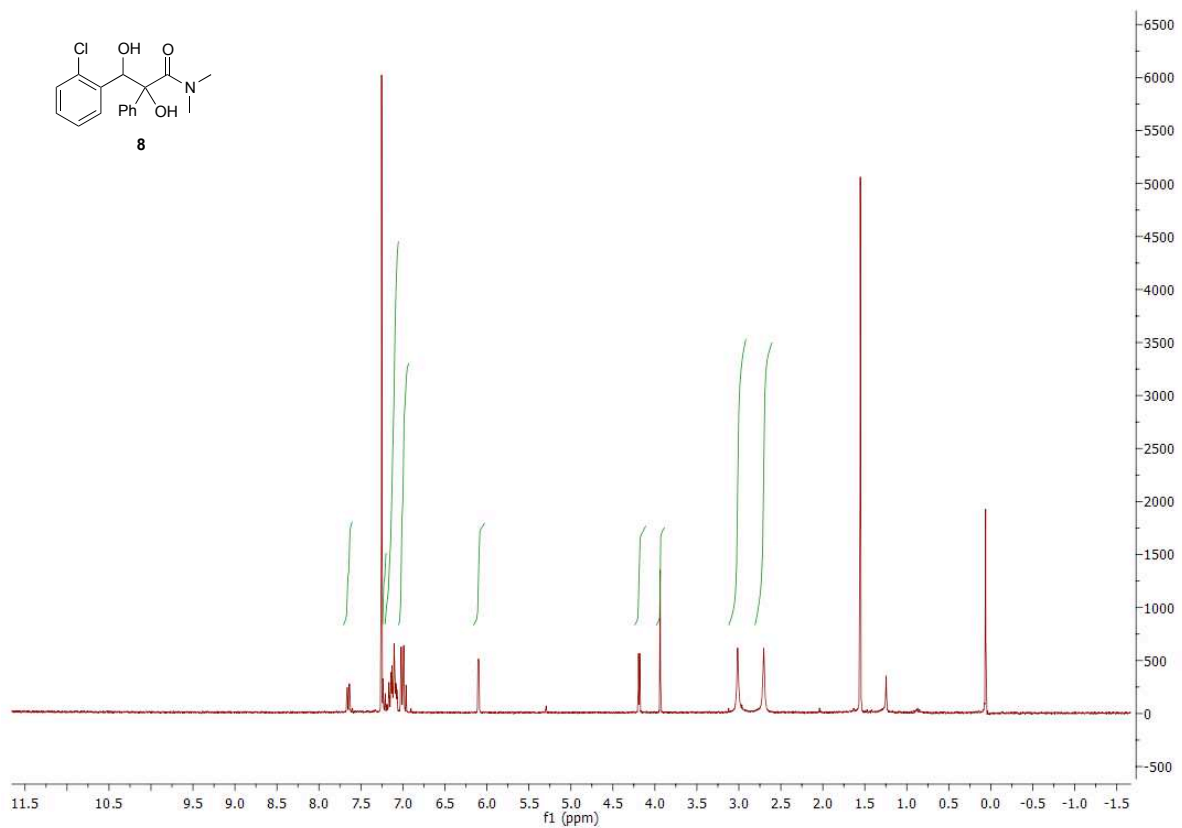
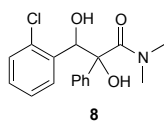
^1H (300 MHz) and ^{13}C (75 MHz) spectra (CDCl_3) of 3ba

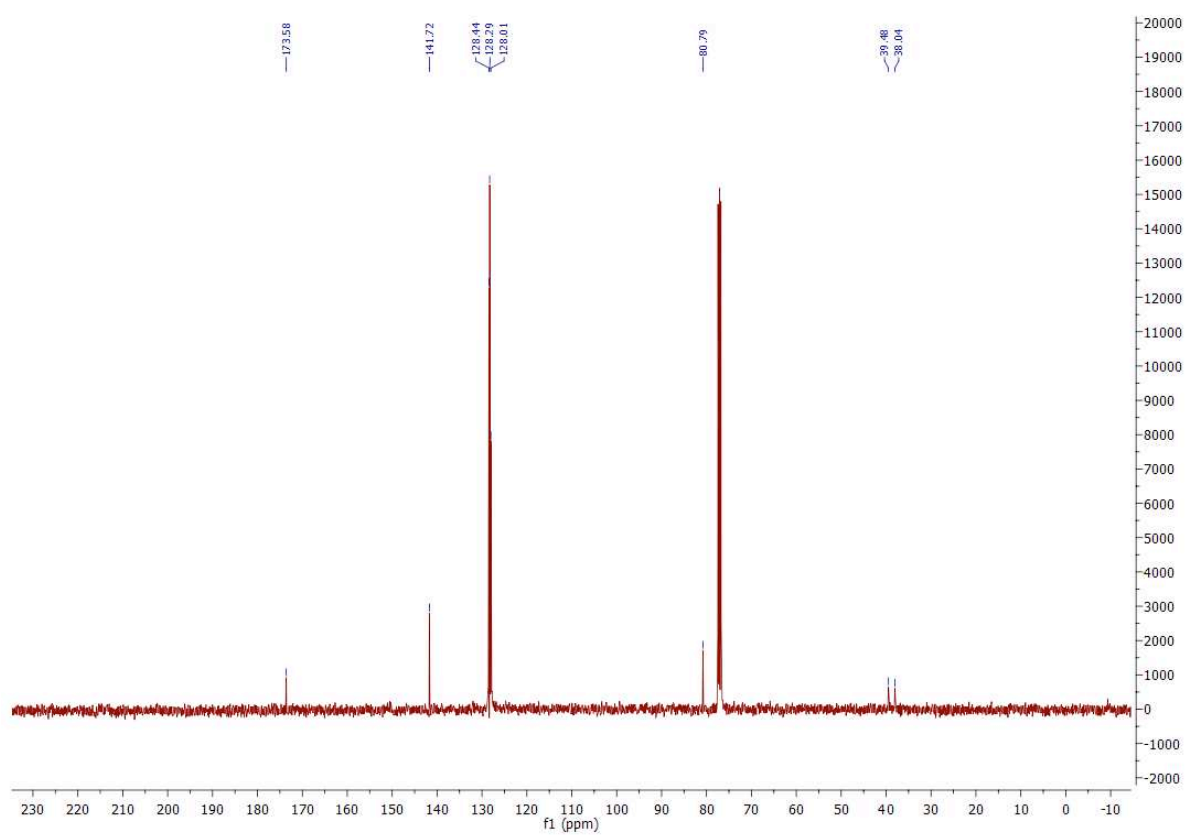
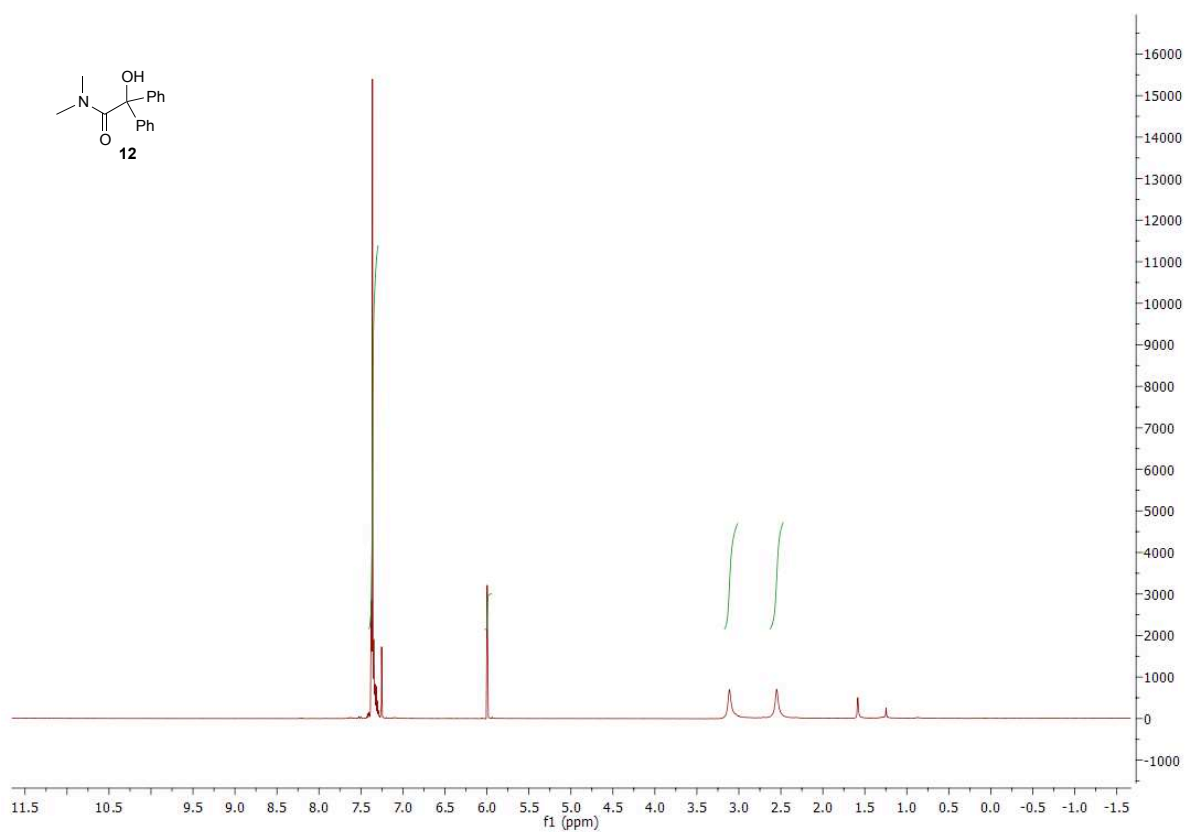
^1H (300 MHz) and ^{13}C (75 MHz) spectra (CDCl_3) of **6**

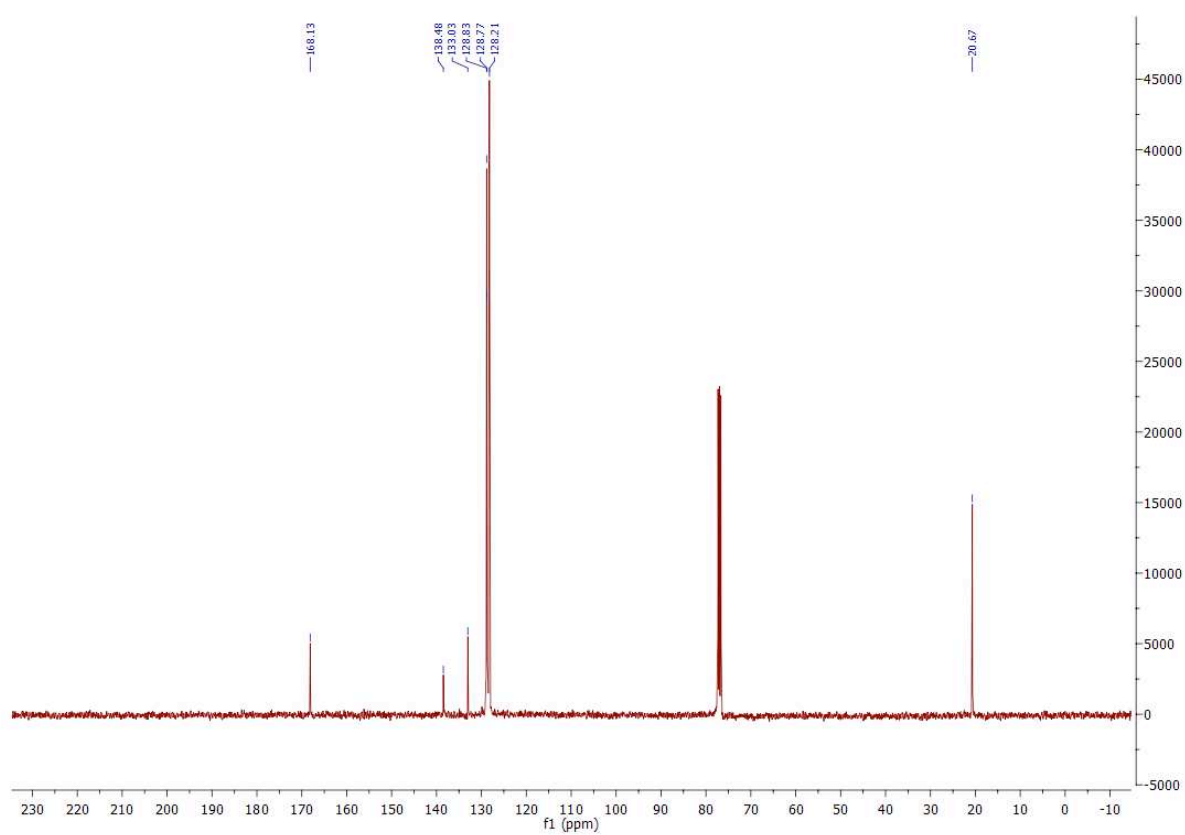
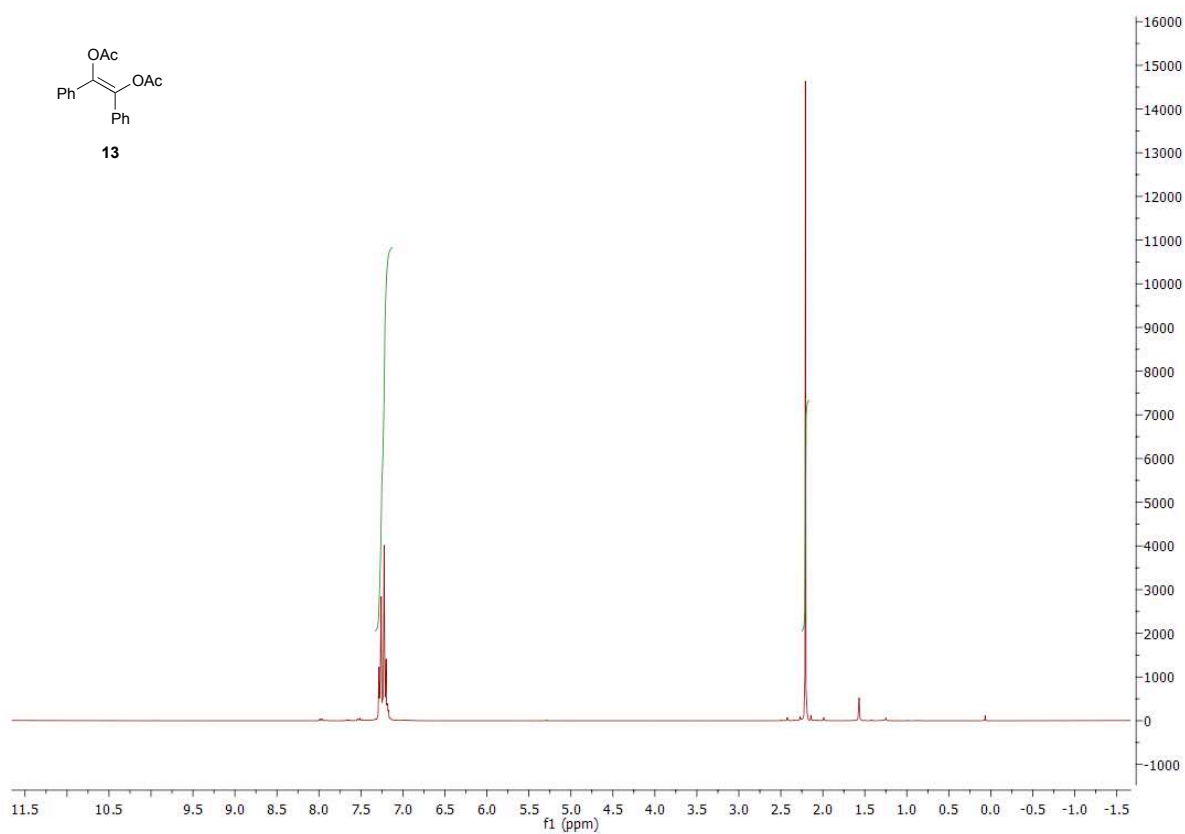
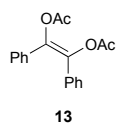


^1H (300 MHz) and ^{13}C (75 MHz) spectra (CDCl_3) of **7**



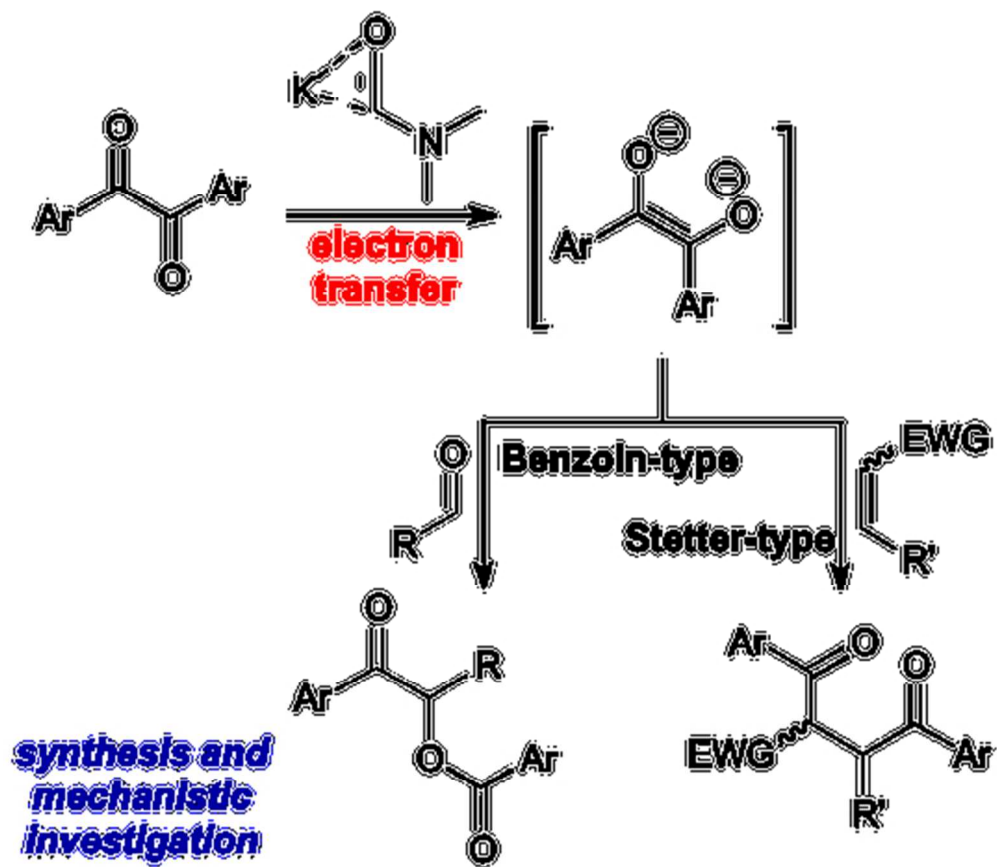
^1H (300 MHz) and ^{13}C (75 MHz) spectra (CDCl_3) of **8**

^1H (300 MHz) and ^{13}C (75 MHz) spectra (CDCl_3) of 12

^1H (300 MHz) and ^{13}C (75 MHz) spectra (CDCl_3) of **13**

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The KO^tBu-DMF system promotes benzoin- and Stetter-like reactions of alpha-diketone donors through a double electron-transfer-based mechanism