Phase transfer catalyzed conjugate addition-initiated ring-closure (CAIRC) reactions with 2-bromo-2-cyclopentenones

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Abstract

When 2-bromo-2-cyclopentenone is treated with various carbon nucleophiles containing active methylenes, it undergoes a conjugate addition initiated-ring closure (CAIRC) reaction. This leads to the formation of carbon- and heterocyclic compounds in a regioselective fashion with good to high yield. Several bases and phase transfer catalysts were investigated. CsF-Si(OEt)₄ as base together with benzylidimethyl (2-hydroxyethyl)-ammonium chloride, C₆H₅CH₂N(Cl)(CH₃)₂CH₂CH₂OH, as phase transfer catalyst, were found to be mild and efficient reagents for carrying out the synthetic transformation

Keywords: Dihydropyranocoumarins, dihydrofurans, cyclopropanes, phase-transfer catalysis, tandem reactions, Michael acceptors, cesium-fluoride, tetraethyl orthosilicate
Introduction

The synthesis of dihydrofurans and their derivatives has been of considerable interest to organic and medicinal chemists for many years as a large number of natural products and drugs contain this heterocyclic nucleus. For example, the dihydrofuran derivatives methyl 3,4-dihydro-2-methyl-4-oxo-2H-furo[3,2-c]chromene-2-carboxylate \( \text{A} \), methyl 2,3,4,5-tetrahydro-2-methyl-4-oxofuro[3,2-c]quinoline-2-carboxylate \( \text{B} \), methyl 8,9-dihydro-9-methyl-7-oxo-7H-phenaleno[1,2-b]furan-9-carboxylate \( \text{C} \), 2-acetylnaphtho[2,3-b]furan-4,9-dione \( \text{D} \) (Figure 1) and others having similar structures have been widely found in nature and they have also been synthesized.\(^1\) Amongst them a wide spectrum of biological activities is exhibited, including antimicrobial, antifungal, anticoagulant, insecticidal, anthelmintic, hypnotic, antidiuretic and antiarrhythmic properties.\(^2\)

![Molecules](image)

**Figure 1**

The development of more pharmacophores on these or related molecules might well lead to compounds with even better biological activity.\(^3,4\) In this regard, annulation methods have proved to be invaluable aids to synthetic chemists in the synthesis of such complex natural and non-natural products as terpenes, steroids, alkaloids and others.\(^5,6\)

The use of CAIRC (conjugate addition initiated-ring closure), particularly phase transfer catalyzed tandem reactions for the synthesis of cyclopropane and dihydrofuran systems have only recently come of age as a simple straightforward one-pot synthesis and often these reactions are carried out under mild basic conditions.\(^7,8\) To a large extent, mild bases suppress the formation of side products, thus improving the yields of the desired products.\(^9\) Nonetheless, in many cases, the yields and scope of the reaction are far from satisfactory due to long reaction times that cause the decomposition of both reactants and products leading to reduced overall isolated yields. Moreover, the scope of the reaction with respect to nucleophiles is also limited since the indicated bases and phase transfer catalysts (PTC) provide no or only trace amounts of products when cyclic and bulky nucleophiles are used.\(^10,11\)

Recently we discovered that CAIRC reactions in the presence of ionic liquids or Lewis acids could catalyze the formation of three and five-membered rings with good to high chemical yields by employing a variety of difunctional compounds.\(^9,10\) Our interest in extending and developing alternative protocols for CAIRC reactions, led us to explore phase-transfer catalysis. We found that a combination of CsF-Si(OEt)\(_4\) as base and BnMe\(_2\)N(Cl)CH\(_2\)CH\(_2\)OH as PTC was effective, giving tandem reaction in reduced reaction times, from days to hours. In particular, the utility of this reaction system is demonstrated by the preparation of polycyclic compounds having more complex structures, such as those listed below (Table 5), from commercially available starting materials.
The present investigation was conducted in four steps: First, the screening of different bases under tetrabutylammonium bromide (TBAB) catalyzed reaction conditions. Second, the study of the influence of several PT catalysts in the presence of K$_2$CO$_3$ as the base. Third, a comparative study between bases (K$_2$CO$_3$-NaHCO$_3$ and CsF-Si(OEt)$_4$) which gave promising results during the screening experiment, step a, in the presence of BnMe$_2$N(Cl)CH$_2$CH$_2$OH catalyst and, finally, investigation of the scope and limitations of the optimized reaction condition, using a wide range of nucleophiles.

**Results and Discussion**

The screening experiments were run with a number of commercially available PT catalysts and several inexpensive and mild inorganic and a few organic bases. By this methodology, both the base and the PTC work in tandem. This led to the development of an efficient protocol. Unless otherwise stated, in all the screening experiments, compounds 1a and 2a-c were used as model reagents. Toluene was used as the organic solvent and the reactions were run at room temperature. The yields obtained in the reaction of 1a with several nucleophiles are given in Tables 1-5 and the reaction mechanism is summarized in Scheme 1.$^9$

![Scheme 1](image)

**Screening of bases**

The effect of several bases on the tandem reaction of difunctional compounds (Figure 2) to 2-bromo-2-cyclopentenone 1a in the presence of TBAB was studied (Table 1).

In this preliminary screening, we tested various organic and inorganic bases. The treatment of 1a with some dicarbonyl compounds at room temperature in toluene in the presence of TBAB and different inorganic
bases gave tandem adducts in 63-88\% isolated yields. However, in the case of organic bases, the yield of the tandem product obtained from 2a was very low. For example, in the presence of Et$_3$N, the yield of 3a obtained was only 15\% compared to 83\% in the presence of K$_2$CO$_3$ (Table 1, Entry 1) using the same reaction conditions. A similar phenomenon was also observed when t-BuOK was used. The reaction mixture with t-BuOK/18-crown-6 was messy; a number of degradation products were formed and we were not able to determine exactly what the product distribution was. We concluded that the higher basicity of alkoxide reagent favors the decomposition of the starting materials.

Based on this information, we continued to survey only inorganic bases such as CsF, Cs$_2$CO$_3$, Li$_2$CO$_3$, K$_2$CO$_3$, NaHCO$_3$, Na$_2$CO$_3$, CsF/Si(OR)$_4$, etc., in the presence of TBAB. Both Si(OEt)$_4$ and Si(OMe)$_4$ were useful but Si(OEt)$_4$ showed slightly better activity than Si(OMe)$_4$. We also tested combinations of different bases to possibly find composite reagents that could improve the conversion.

![Figure 2](image.png)

**Table 1.** Effect of bases in the reaction of 1a with three nucleophiles in the presence of TBAB

<table>
<thead>
<tr>
<th>Entry</th>
<th>Nucleophile</th>
<th>Base</th>
<th>Time/h</th>
<th>Yields/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2a</td>
<td>K$_2$CO$_3$</td>
<td>18</td>
<td>83 (3a)</td>
</tr>
<tr>
<td>2</td>
<td>2a</td>
<td>Cs$_2$CO$_3$</td>
<td>3</td>
<td>67</td>
</tr>
<tr>
<td>3</td>
<td>2a</td>
<td>K$_2$CO$_3$-NaHCO$_3$</td>
<td>14</td>
<td>88</td>
</tr>
<tr>
<td>4</td>
<td>2b</td>
<td>K$_2$CO$_3$</td>
<td>14</td>
<td>81 (3b)</td>
</tr>
<tr>
<td>5</td>
<td>2b</td>
<td>Cs$_2$CO$_3$</td>
<td>2</td>
<td>82</td>
</tr>
<tr>
<td>6</td>
<td>2b</td>
<td>CsF-Si(OEt)$_4$</td>
<td>10</td>
<td>86</td>
</tr>
<tr>
<td>7</td>
<td>2b</td>
<td>Cs$_2$CO$_3$-NaHCO$_3$</td>
<td>2</td>
<td>86</td>
</tr>
<tr>
<td>8</td>
<td>2b</td>
<td>K$_2$CO$_3$-NaHCO$_3$</td>
<td>14</td>
<td>84</td>
</tr>
<tr>
<td>9</td>
<td>2c</td>
<td>K$_2$CO$_3$</td>
<td>20</td>
<td>77 (3c)</td>
</tr>
<tr>
<td>10</td>
<td>2c</td>
<td>Cs$_2$CO$_3$</td>
<td>3</td>
<td>63</td>
</tr>
<tr>
<td>11</td>
<td>2c</td>
<td>Cs$_2$CO$_3$-NaHCO$_3$</td>
<td>3</td>
<td>69</td>
</tr>
<tr>
<td>12</td>
<td>2c</td>
<td>CsF-Si(OEt)$_4$</td>
<td>12</td>
<td>72</td>
</tr>
<tr>
<td>13</td>
<td>2c</td>
<td>K$_2$CO$_3$-NaHCO$_3$</td>
<td>20</td>
<td>84</td>
</tr>
</tbody>
</table>

As summarized in Table 1, the best yields were obtained when reactions were mediated by Cs$_2$CO$_3$, K$_2$CO$_3$-NaHCO$_3$, and CsF-Si(OEt)$_4$ (TEOS). The reactions went to completion in a short time (2-4 h) when Cs$_2$CO$_3$ or Cs$_2$CO$_3$-NaHCO$_3$ were used. However, we found that Cs$_2$CO$_3$ mediated reactions also gave byproducts. The undesirable side reactions decreased the yields of the target adducts and rendered their purification difficult. Especially, this was a serious problem when the nucleophiles contained ester functionalities (Table 1, entries 2, 10, 11). Better results were obtained by employing either CsF-Si(OEt)$_4$ or K$_2$CO$_3$-NaHCO$_3$. Although the combination of K$_2$CO$_3$ and NaHCO$_3$ or CsF and Si(OEt)$_4$ could lead to a drastic increase in rate of reaction and yield, neither of the bases alone was sufficiently effective to carry out the tandem reaction independently with
TBAB as a phase-transfer catalyst. The tandem reaction did not proceed at all with NaHCO$_3$ and TBAB; only the starting materials were recovered even after prolonged reaction times.

**Screening of PT Catalysts**

To achieve an increased conversion rate, we further examined the effects of the PT catalysts on the tandem reaction using a selection of catalysts in the presence of 2a and K$_2$CO$_3$ (Scheme 2). The reason for choosing K$_2$CO$_3$ as a base in this screening was that K$_2$CO$_3$ is better with TBAB and any improvement using other catalysts could properly be associated with the activity of these catalysts. The performance of nine PT catalysts was compared (Table 2). The use of BnMe$_2$N(Cl)CH$_2$CH$_2$OH resulted in a unique and a remarkable increase in the rates of product formation and significantly enhanced chemical yield (Table 2, entry 5) while other catalysts such as THAB and TBABF were less effective, but still promising (Table 2, entries 2 and 3). Particularly, the catalytic effect of TBAB decreased when structurally more complex nucleophiles were used (Table 2, entry 1).

![Scheme 2](image)

**Table 2.** The role of different PT catalysts in the reaction of 1a with 2a in the presence of K$_2$CO$_3$

<table>
<thead>
<tr>
<th>Entry</th>
<th>PT catalyst</th>
<th>Yields/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TBAB</td>
<td>46</td>
</tr>
<tr>
<td>2</td>
<td>THAB</td>
<td>69</td>
</tr>
<tr>
<td>3</td>
<td>TBABF</td>
<td>67</td>
</tr>
<tr>
<td>4</td>
<td>TBAI</td>
<td>54</td>
</tr>
<tr>
<td>5</td>
<td>BnMe$_2$N(Cl)CH$_2$CH$_2$OH</td>
<td>81</td>
</tr>
<tr>
<td>6</td>
<td>BnN(Cl)Et$_3$</td>
<td>58</td>
</tr>
<tr>
<td>7</td>
<td>Bu$_4$NHSO$_4$</td>
<td>41</td>
</tr>
<tr>
<td>8</td>
<td>BnP(Cl)Ph$_3$</td>
<td>52</td>
</tr>
<tr>
<td>9</td>
<td>TBAF</td>
<td>34</td>
</tr>
</tbody>
</table>

TBAB = tetrabutylammonium bromide, THAB = tetrahexylammonium bromide, TBABF = tetrabutylammonium tetrafluoroborate, TBAI = tetrabutylammonium iodide, TBAF = tetrabutylammonium fluoride. The reaction time was 14h in each case.

Although THAB afforded a reasonable yield, it required a longer reaction time since 1,4-adducts 5 were formed first and then slowly converted into the corresponding tandem products (Scheme 3). Fortunately, this was not found when a reactant like 2c that gave cyclopropanes was employed.
Although the detailed mechanism of the reaction is not known with certainty, we interpret our findings as follows: The quaternary ammonium ion Q⁺ from PTC coordinates to two O-atoms forming a stable six-membered enolate. Thus, the catalyst functions in the formation of the desired product in the following ways: a) transfer of the enolate from an inter-phase to an organic phase and b) reaction of the enolate with the acceptor in the organic phase. Thus, the superior efficiency of BnMe₂N(Cl)CH₂CH₂OH could be interpreted in terms of organophilicity and accessibility of the lipophilic cation Q⁺ of the catalyst. In other words, the PT agent must have enough lipophilicity to be able to partition the nucleophilic anion into the organic phase and the cation-anion interaction should be loose enough to ensure high anionic reactivity.

Comparative studies of CsF-Si(OEt)₄ and K₂CO₃-NaHCO₃ as bases
After finding that BnMe₂N(Cl)CH₂CH₂OH is the catalyst of choice for promoting our reactions, we applied this process to a series of nucleophiles to determine the scope and limitations with the base systems, K₂CO₃-NaHCO₃ and CsF-Si(OEt)₄. We found that the reaction rates were high and the chemical yields were increased by a factor of 1-2 when the tandem reaction was performed using simple, acyclic nucleophiles in the presence of either K₂CO₃-NaHCO₃ or CsF-Si(OEt)₄ (Tables 3 and 4). However, it should be emphasized that K₂CO₃-NaHCO₃ became less efficient as the complexity of the nucleophile increased and, in most cases, CsF-Si(OEt)₄ afforded distinctly superior results in shorter reaction times.

Although the synthesis of dihydrofurans using the K₂CO₃-NaHCO₃ procedure was found to be useful for a range of acyclic nucleophiles, it afforded poor yields with the cyclic analogs. For example, 2f gave only 10 % conversion after 12 h of stirring (Table 3, entry 6) and attempts to perform the reaction with 2h-2k failed. Surprisingly, 2g gave a high yield of the corresponding dihydrofuran in the presence of K₂CO₃-NaHCO₃ (Table 3, entry 7). This exceptional reactivity of 2g towards 1a was also observed during ionic liquid promoted synthesis of dihydrofurans. Reaction of 1a with β-diesters like 2c was slow and complete conversion was obtained only after 24 h in the presence of K₂CO₃-NaHCO₃ (Table 3, entry 3).

Scope and limitations using CsF-Si(OEt)₄
In this investigation, the efficiency of CsF-Si(OEt)₄ can be explained as: electron density at Si decreases with extra-coordination, causing the electropositive character (Lewis acidity) of the silicon center to be increased. In addition, electronegative substituents can also lower the energy of the 3d atomic orbitals, which facilitates the formation of hypervalent silicon compounds. As outlined in Scheme 4, silicon can adopt 4, 5 and 6 coordinate complexes (Scheme 4). Nucleophilicity of ligands, particularly R, attached to Si center increases from 4 to 6-coordinate complexes.
Table 3. Effects of K$_2$CO$_3$-NaHCO$_3$ on the Michael acceptor 1a and donors in the presence of BnMe$_2$(Cl)CH$_2$CH$_2$OH

<table>
<thead>
<tr>
<th>Entry</th>
<th>Nucleophile</th>
<th>Time/h</th>
<th>Product</th>
<th>Yields/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>OMe</td>
<td>5</td>
<td>3a</td>
<td>59</td>
</tr>
<tr>
<td>2</td>
<td>OMe</td>
<td>5</td>
<td>3b</td>
<td>65</td>
</tr>
<tr>
<td>3</td>
<td>MeO</td>
<td>24</td>
<td>3c</td>
<td>61</td>
</tr>
<tr>
<td>4</td>
<td>NC</td>
<td>5</td>
<td>3d</td>
<td>81</td>
</tr>
<tr>
<td>5*</td>
<td>NC</td>
<td>5</td>
<td>3e</td>
<td>82</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>12</td>
<td>3f</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>12</td>
<td>3g</td>
<td>83</td>
</tr>
</tbody>
</table>

*a A single diastereomer was obtained

Scheme 4

Accordingly, Si(OEt)$_4$ is a prototypical alkoxide and its applications exploit the reactivity of the Si-OR bonds. The catalytic effect of F$^-$ involves the displacement of an OR via an Sn2-Si mechanism followed by preferential

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abstraction of a proton from the base by the RO\(^-\). In addition to biphasic activity, the PTC can also temporarily coordinate with the reagents as a Lewis acid to facilitate proton abstraction (Scheme 5).\(^{16}\)

**Possible mechanism for CsF-Si(OEt)\(_4\) mediated CAIRC reactions**

![Scheme 5](image)

After having identified a suitable base system and an efficient PT catalyst that afforded efficient conversion, the reactions between 1a or 1b and a range of nucleophiles 2a-2k were run. Across this range of nucleophiles, the yields and rate of conversion were uniformly good (Table 4).

When 1a was treated with 2a in the presence of CsF-Si(OEt)\(_4\) and a catalytic amount of BnMe\(_2\)N(Cl)CH\(_2\)OH, methyl 4,5,6,6a-tetrahydro-2-methyl-6-oxo-3aH-cyclopenta[b]furan-3-carboxylate 3a was formed in good yield (Table 4, entry 1). Likewise, when 2b was treated with 1a, only the corresponding dihydrofuran 3b was isolated in quantitative yields. As shown in Table 4, entries 3, 4 & 5, the reaction of 2c, 2d and 2e with 1a also proceeded smoothly to give the desired cyclopropane derivatives 3c, 3d and 3e, respectively, with relatively short reaction times. Particularly, 2e undergoes a highly diastereoselective reaction to give only one isomer of 3e.

Based on these findings, we have extended our study of the reaction of compound 1a with cyclic \(\beta\)-dicarbonyl compounds such as 2f and 2g as a possible means for the synthesis of tricyclic dihydrofuran adducts 3f and 3g. The yields obtained were good (Table 5, entries 1 and 2). The superiority of CsF-Si(OEt)\(_4\) and BnMe\(_2\)N(Cl)CH\(_2\)CH\(_2\)OH over other combinations for the tandem reaction was further demonstrated by using some other representative bulky nucleophiles, 2h-2k (Figure 3), which led to the preparation of dihydrofurocoumarin and other derivatives of natural products (Scheme 6). Due to solubility problems with some of the nucleophiles, acetonitrile was used as a solvent instead of toluene in the reaction between 1a, 1b and 4-hydroxycoumarin 2h, 2,4-quinolinediol 2i, 3-hydroxy-1H-phenalen-1-one 2j and 2-hydroxy-1,4-naphthoquinone 2k.
Table 4. Effects CsF-Si(OEt)$_4$ on the Michael acceptors 1a, 1b and a range of donors in the presence of BnMe$_2$N(Cl)CH$_2$CH$_2$OH

<table>
<thead>
<tr>
<th>Entry</th>
<th>Nucleophile</th>
<th>Time/h</th>
<th>Product</th>
<th>Yields/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>OOMe</td>
<td>3</td>
<td>3a</td>
<td>89</td>
</tr>
<tr>
<td>2</td>
<td>2b</td>
<td>3</td>
<td>3b</td>
<td>84</td>
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<td>3</td>
<td>OOMe2c</td>
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<td>4</td>
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<td>3d</td>
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<td>5</td>
<td>OOMe2e</td>
<td>2</td>
<td>3e</td>
<td>87</td>
</tr>
</tbody>
</table>

Figure 3

For instance, the reaction of 1a with 2h and 2i gave the potentially biologically interesting dihydrofurcoumarin 3h and dihydrofuroquinolinone derivative 3i in 58 and 56% yields, respectively, without formation of any regioisomers (Table 5, entries 3 and 4). Treatment of 2j with 1a gave the expected dihydrofuraphenalone 3j in high yield and in a reasonably short time (Table 5, entry 5). Similarly, 2h reacted with 2-bromo-2-cyclohexenone 1b to furnish 4h in 61% yield. The nucleophiles 2i, and 2j also reacted smoothly with 1b as Michael acceptor under the same conditions to give 4i, and 4j in 59 and 87% isolated yields, respectively (Scheme 6). Surprisingly, when 1a and 1b were treated with 2k, dihydrofuronaphthoquinone adducts 3k and 4k were obtained (Table 5, entries 6 and 10). They were, however, highly unstable and decomposed into nonhomogenous mixtures upon attempted isolation. They could only be identified by GC-MS.
Scheme 6

The longer reaction times required for cyclic compounds compared to those of acyclic β-diketones could be explained as a result of formation of unstable complexes due to steric compression or due to increased negative charge delocalization. In general, the results in Table 5 indicate that CsF-Si(OEt)$_4$ with BnMe$_2$N(Cl)CH$_2$CH$_2$OH is the most efficient combination that can be applied to a wide range of reagents, particularly for diesters and cyclic nucleophiles and it provides a rapid route for the preparation of a variety of polycycles and heterocycles.

Table 5. Effects of CsF-Si(OEt)$_4$ on the Michael acceptors 1a, 1b and range of donors (2f-2k) in the presence of BnMe$_2$N(Cl)CH$_2$CH$_2$OH

<table>
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<tr>
<th>Entry</th>
<th>Acceptor</th>
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<th>Yield/%</th>
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<td>1a</td>
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<td>12</td>
<td><img src="3f" alt="Product Image" /></td>
<td>81</td>
</tr>
<tr>
<td>2</td>
<td>1a</td>
<td></td>
<td>9</td>
<td><img src="3g" alt="Product Image" /></td>
<td>85</td>
</tr>
<tr>
<td>3</td>
<td>1a</td>
<td></td>
<td>18</td>
<td><img src="3h" alt="Product Image" /></td>
<td>58</td>
</tr>
<tr>
<td>4</td>
<td>1a</td>
<td></td>
<td>18</td>
<td><img src="3i" alt="Product Image" /></td>
<td>56</td>
</tr>
<tr>
<td>5</td>
<td>1a</td>
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<tr>
<td>6</td>
<td>1a</td>
<td></td>
<td>18</td>
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Table 5. Continued

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<th>Time/h</th>
<th>Products</th>
<th>Yield/%</th>
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<tr>
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<td>8</td>
<td>1b</td>
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<td><img src="image" alt="Products 4k" /></td>
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</tbody>
</table>

Conclusions

Since tandem transformation is among the most efficient synthetic routes, development of reaction conditions that use non-toxic, readily available, mild and economic reagents with operational simplicity could contribute to the creation of environmentally benign processes. To this end, we have demonstrated that CsF-Si(OEt)₄ and BnMe₂N(Cl)CH₂CH₂OH mediated reactions are simple, efficient, clean, highly regioselective processes that give high yields with structurally diverse difunctionals reagents such as β-diesters, β-diketones, β-ketoesters, nitroesters, malononitriles, and cyanoesters in reasonable reaction times. They give single products and in these cases no further purification was necessary. An advantage of using CsF-Si(OEt)₄ is also that it is not necessary most to use a stoichiometric amount of CsF; only 20 mol% and a stoichiometric amount of Si(OEt)₄ is sufficient to give the reaction. In CsF-Si(OEt)₄ mediated reactions, Si(OEt)₄ plays two roles: First, generation of a strong base, C₂H₅O⁻, capable of deprotonating the difunctional compound, which is promoted by coordination of F⁻ to the Si-compound. Second, trapping of the enolate adduct by the silyl enol ether and then transfer of the Michael acceptor for 1,4-addition to occur.

The reaction system could probably be further extended for the regioselective synthesis of naturally occurring and biologically active polycyclic compounds containing the dihydrofuran motif, which are otherwise difficult to prepare by other methods. To the best of our knowledge, this is the first example of a general base mediated PT catalyzed tandem reaction of various dicarbonyl compounds to enones.

Experimental Section

General. All ¹H and ¹³C NMR spectra were recorded on a JEOL JNM-EX 400 FT-NMR system using CDCl₃ as a solvent at room temperature. Chemical shifts are given in ppm and J-values in Hz. Analytical TLC were carried...
out on precoated (0.25 mm) Merck silica gel F-254 plates. Flash chromatography was carried out using matrix silica (Si-60 Å 35-70 μm). GLC analyses were performed on a Varian 3300 chromatograph equipped with split injector, FID detector and a Varian 4400 integrator. IR spectra were recorded on a FT-IR spectrometer and are reported as wave number. GC-MS spectra were registered on a Hewlett 5890 Packard series II CP Sil 5 CB column (25 m) followed by VG Quattro mass spectrometer. A Finnigan-MAT-95XL mass spectrometer was used to obtain HREIMS data and the spectra were obtained at 250 °C and 70 eV. All reagents and solvents except 2-bromoenones 1 were obtained from commercial sources and used as received without further purification. 2-Bromoenones 1a,b were prepared according to literature procedure.13

**General procedure for the screening experiments.** A mixture of 1a or 1b (1.0 mmol), a reagent 2a-c (1.25 mmol), a base (1 mmol) and PT catalyst (15 mmol %) in toluene (5 mL) was stirred for the specified time at room temperature (Tables 1 and 2). The organic product was extracted with Et2O. The combined organic layers were washed with brine and dried over Na2SO4. The solvent was removed in vacuo and the residue purified with column chromatography using appropriate solvents to get the required products.

**Procedure for the reaction of 2-bromoenones (1a and 1b) with various carbon nucleophiles 2a-2k.** A mixture of 1 (1.0 mmol) and a reagent 2 (1.25 mmol) in the presence of CsF (20.0 mmol %), Si(OEt)4 (1 mmol) and BnMe2N(Cl)CH2CH2OH (15.0 mmol%/ in toluene or CH3CN (5ml) was stirred for the specified time at room temperature (Table 4). The organic product was extracted with EtOAc or CHCl3 (3x). The combined organic layers were washed with brine and dried over Na2SO4. The solvent was removed in vacuo and the residue purified with column chromatography using appropriate solvents to get the required products. Products 3a-3g have been known but 3h-3j and 4h-4j were unknown compounds9 and their spectral data are given below.

**7,8-Dihydro-6bH,9aH-5,10-dioxapentaleno[2,1-a]naphthalene-6,9-dione (3h).** Yield 0.142 g, 58%; brown powder, Rp 0.41 (4:1 EtOAc/CHCl3); mp 294-295 °C. IR (neat, NaCl plates, v max cm⁻¹): 3143, 2995, 1732, 1715, 1645, 1569, 1382; 1H NMR: δ 2.46-2.61 (m, 2H), 2.68-2.75 (m, 2H), 4.20-4.38 (m, 1H), 5.13 (d, J 8.8Hz, 1H), 7.19 (t, J 10.0 Hz, 1H), 7.29-7.49 (m, 1H), 7.61 (t, J 6.8, 1H), 7.71 (dd, J 6.4 & 1.2Hz, 1H); 13C NMR: δ 24.6 (CH2), 33.5 (CH2), 42.0 (CH), 87.6 (CH), 112.3 (C), 124.1 (CH), 124.8 (CH), 127.5 (C), 130.1 (CH), 133.9 (CH), 155.4 (C), 160.2 (C), 163.3 (COO-), 202.4 (CO). HRMS found for C14H10O4: 242.0578. calcld: 242.0579.

**5,6b,7,8-Tetrahydro-9aH-10-oxa-5-aza-pentaleno[2,1-a]naphthalene-6,9-dione (3i).** Yield 0.137 g, 56%, white powder, Rp 0.38 (4:1 EtOAc/CHCl3), mp 400-402 °C. IR (neat, NaCl plates, v max cm⁻¹): 3155, 2982, 1735, 1697, 1658, 1563, 1335, 1307, 1221; 1H NMR: δ 2.18-2.24 (m, 2H), 2.28-2.45 (m, 2H), 4.33-4.46 (m, 1H), 5.06 (d, J 8.8Hz, 1H), 6.45 (d, J 10.0Hz, 1H), 7.38-7.54 (m, 1H), 7.50 (t, J 6.4Hz, 1H), 7.73 (d, J 8.0Hz, 1H), 11.85 (s, 1H); 12C NMR: δ 23.7 (CH2), 35.1 (CH2), 41.8 (CH), 85.9 (CH), 108.9 (C), 112.2 (C), 116.4 (CH), 122.7 (CH), 123.0 (CH), 126.4 (CH), 131.6 (C), 154.2 (C), 163.4 (CON), 213.2 (CO); HRMS found for C14H12O5: 241.0731. calcld: 241.0738.

**8,9-Dihydrocyclopenta[d]phenaleno[1,2-b]furan-7,10(7b,10aH)-dione (3j).** Yield 0.234 g, 84 %, yellow solid; Rp 0.34 (4:1 EtOAc/CHCl3), mp 356-358.6 °C. IR (neat, NaCl plates, v max cm⁻¹): 3181, 2991, 1745, 1728, 1673, 1560, 1475, 1320; 1H NMR: δ 2.22-2.36 (m, 2H), 2.38-2.47 (m, 2H), 4.23-4.30 (m, 1H), 5.04 (d, J 9.2Hz, 1H), 7.53 (t, J 7.8Hz, 1H), 7.67-7.89 (m, 2H), 8.06-8.16 (m, 2H), 8.62 (d, J 7.6Hz, 1H); 13C NMR: δ 24.9 (CH2), 36.3 (CH2), 43.0 (CH), 86.8 (CH), 110.5 (C), 127.3 (2xCH), 128.1 (2xCH), 128.4 (C), 129.3 (C), 131.2 (C), 133.1 (CH), 133.8 (C), 134.6 (CH), 135.7 (C), 161.8 (CO), 202.6 (CO). HRMS found for C18H12O3: 276.0787. calcld: 276.0786.

**6a,8,9,10a-Tetrahydro-7H-benzo[4,5]furo[3,2-c]chromene-6,10-dione (4h).** Yield 0.157 g, 61%, brown solid, Rp 0.46 (3:2 EtOAc/CHCl3), mp 319-321.4 °C. IR (neat, NaCl plates, v max cm⁻¹): 3153, 2999, 1730, 1718, 1642, 1560, 1382, 1192; 1H NMR: δ 1.92-2.06 (m, 2H), 2.18-2.38 (m, 2H), 2.52-2.64 (m, 2H), 4.10-4.15 (m, 1H), 5.29 (d, J 10.0Hz, 1H), 7.10 (d, J 7.6 Hz, 1H), 7.20-7.34 (m, 1H), 7.48 (t, J 6.8Hz, 1H), 7.80 (dd, J 7.6 & 1.3Hz, 1H);
$^{13}$C NMR: δ 21.7 (CH$_2$), 25.2 (CH$_2$), 38.1 (CH$_2$), 42.9 (CH), 87.8 (CH), 104.3 (C), 112.3 (C), 117.3 (CH), 124.2 (CH), 124.5 (CH), 129.8 (CH), 133.2 (CH), 156.0 (C), 168.4 (COO), 206.2 (CO); HRMS found for C$_{13}$H$_{12}$O$_4$: 256.0739. calcd: 256.0736.

6a,8,9,10a-Tetrahydro-5H,7H-11-oxo-5-azabenzo[a]fluorene-6,10-dione (4i). Yield 0.152 g, 59%, white solid, R$_f$ 0.40 (3:2 EtOAc/CHCl$_3$), mp 413-415 °C. IR (neat, NaCl plates, $v_{\text{max}}$, cm$^{-1}$): 3142, 2988, 1728, 1703, 1655, 1543, 1321, 1287; $^1$H NMR: δ 1.94-2.13 (m, 2H), 2.20-2.32 (m, 2H), 2.56-2.65 (m, 2H), 4.18-4.32 (m, 1H), 5.26 (d, $J$ 9.6Hz, 1H), 7.20 (t, $J$ 7.2 Hz, 1H), 7.46-7.51 (m, 1H), 7.65 (t, $J$ 6.8Hz, 1H), 7.78 (d, $J$ 8.0Hz, 1H), 11.55 (s, 1H); $^{13}$C NMR: δ 21.7 (CH$_2$), 25.2 (CH$_2$), 38.1 (CH$_2$), 42.9 (CH), 87.8 (CH), 117.3 (C), 124.2 (CH), 124.5 (CH), 129.8 (CH), 133.2 (CH), 156.0 (C), 168.4 (COO), 206.2 (CO); HRMS found for C$_{15}$H$_{12}$O$_4$: 256.0739. calcd: 256.0736.

7a,9,10,11a-Tetrahydro-8H-12-oxaindeno[2,1-a]phenalene-7,11-dione (4j). Yield 0.255 g, 87%, yellow powder, R$_f$ 0.37 (3:2 EtOAc/CHCl$_3$), mp 370-371.8 °C. IR (neat, NaCl plates, $v_{\text{max}}$, cm$^{-1}$): 3181, 3001, 1738, 1726, 1673, 1585, 1465, 1321, 1230; $^1$H NMR: δ 1.94-2.13 (m, 2H), 2.20-2.34 (m, 2H), 2.39-2.48 (m, 2H), 4.25-4.32 (m, 1H), 5.04 (d, $J$ 9.2Hz, 1H), 7.51 (t, $J$ 7.8Hz, 1H) 7.58-7.72 (m, 2H), 8.07-8.17 (m, 2H), 8.64 (d, $J$ 7.6Hz, 1H); $^{13}$C NMR: δ 21.8 (CH$_2$), 25.2 (CH$_2$), 36.4 (CH$_2$), 43.3 (CH), 88.1 (CH), 117.8 (C), 124.2 (CH), 124.6 (CH), 126.9 (CH), 133.2 (CH), 140.6 (C), 161.5 (C), 164.3 (CO), 207.8 (CO); HRMS found for C$_{19}$H$_{14}$O$_3$: 290.0944. calcd: 290.0945.

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