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## SmCp<sup>R</sup><sub>2</sub>-mediated cross-coupling of allyl and propargyl ethers with ketoesters and a telescoped approach to complex cycloheptanols<sup>+</sup>

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A highly regio- and diastereoselective cross-coupling of allyl/ propargyl ethers and  $\delta$ -ketoesters, mediated by SmCp<sup>R</sup><sub>2</sub> reagents, delivers decorated  $\delta$ -lactones. Screening of the Cp ligands on Sm(II) was employed to achieve high regio and diastereocontrol in some cases. Crucially, Sml<sub>2</sub> gave unsatisfactory results in the transformation. The process has been exploited in a telescoped approach to complex cycloheptanols in which two Sm(II) reagents act in turn on the simple starting materials.

The latter half of the twentieth century saw the emergence of a new generation of metallic reductive ET reagents<sup>1</sup> for substrate activation.<sup>2</sup> At the vanguard of this new order was samarium(II) iodide  $(SmI_2, Kagan's reagent)^3$  and since its first use in synthesis by Kagan,<sup>4</sup> it has become indispensable.<sup>5</sup> Unfortunately, some  $SmI_2$ -mediated processes proceed with unsatisfactory levels of stereo- and regiocontrol and the identification of alternative Sm(I) reagents that deliver improved results is desirable.<sup>3-5</sup>

δ-Lactones are important building blocks for synthesis and are motifs found in many bioactive targets.<sup>6</sup> Inspired by the seminal studies of Evans on the properties of SmCp\*<sub>2</sub><sup>7</sup> and of Kagan<sup>8</sup> and Takaki<sup>9</sup> on the allylation of simple, unfunctionalised ketones using SmCp<sub>2</sub> and SmCp\*<sub>2</sub>(THF)<sub>2</sub>, respectively, we envisaged a route to lactones **1** from allyl ethers **2** and δ-ketoesters **3** (Scheme 1). In stark contrast to SmI<sub>2</sub>, SmCp<sup>R</sup><sub>2</sub> reagents have found limited use in preparative organic synthesis as ET reagents despite applications in organometallic synthesis and polymer science.<sup>7–10</sup> Crucially, SmI<sub>2</sub> proved to be unreactive towards allyl ethers and gave unsatisfactory results with allylic halides in the proposed coupling-lactonisation: δ-lactones were obtained with poor regio- and diastereocontrol.<sup>11</sup> Herein, we describe the optimisation of a SmCp<sup>R</sup><sub>2</sub>-mediated approach to decorated  $\delta$ -lactones 1 from allyl and propargyl ethers 2 and  $\delta$ -ketoesters 3.<sup>12</sup> To our knowledge, this is the first study examining the influence of substituents on the Cp ring on SmCp<sup>R</sup><sub>2</sub>-mediated C–C bond-formation. Furthermore, we report a telescoped approach to complex cycloheptanols 4 (Scheme 1).

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We began by preparing a family of  $\text{SmCp}^{\text{R}}_2$  reagents **5a-f**, including novel complexes **5c**, **5e** and **5f**, with varying steric and electronic properties (Scheme 2). In line with Takaki's findings,<sup>9</sup> the high reducing ability of **5a,b,e,f** allowed readily prepared and stable allyl/propargyl ethers **2** to be used as substrates in the reductive cross-coupling ( $\text{SmI}_2$ -THF, *ca.* –1.8 V *vs.* SCE;  $\text{SmI}_2$ -H<sub>2</sub>O, *ca.* –2.2 V *vs.* SCE;  $\text{SmCp}^*_2(\text{THF})_2$ , –2.2 V *vs.* SCE).<sup>13</sup> We therefore used the coupling-lactonisation of **2a** and bifunctional ketone **3a** to evaluate the  $\text{Sm}(\text{II})\text{Cp}^{\text{R}}_2$  complexes with the aim of identifying a Sm(II) reagent capable of mediating a regio- and diastereoselective process. Notably, the use of  $\text{SmCp}^{\text{R}}_2$ reagents allowed flexibility with regard to solvent choice –  $\text{SmI}_2$  is almost exclusively used in THF – and toluene was found to provide optimal reactivity and selectivity in the coupling.

Pleasingly, Sm(II) reagents **5a,b** and **5e,f** gave the desired lactone isomer **1a** with high regiocontrol and with a preference for the formation of *anti*-**1a**, as confirmed by X-ray crystallographic



Scheme 1 A SmCp<sup>R</sup><sub>2</sub>-mediated approach to decorated  $\delta$ -lactones: reductive coupling of allyl/propargyl ethers and  $\delta$ -ketoesters. A telescoped approach allows access to complex cycloheptanols.

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**Scheme 2** Tailoring the  $SmCp_2^R$  reagent for the regio- and diastereoselective coupling-lactonisation to give *anti*-**1a**. The minor regioisomer is **1a**' (not shown).

analysis (Scheme 2).<sup>14</sup> A proposed mechanism for the coupling is shown in Scheme  $3.^9$ 

To control the reactivity of allylic samarium(III) intermediate 6a, we proposed that larger Cp ligands would favour reaction through  $\eta^1$  organosamarium(III) **6c** via transition structure 7 to give the desired branched product 8. However, if the Cp ligands were too large, the cyclic transition structure 7 may be disrupted and diastereocontrol lost. As the use of SmCp\*2(THF)2 5a gave anti-1a with moderate dr 83:17, we fine-tuned the steric characteristics of the SmCp<sup>R</sup><sub>2</sub> reagents by varying the nature and number of silvlsubstituents on the Cp ligands. While bis-TMSCp ligands in 5b (TMS - trimethylsilyl) gave excellent regiocontrol, lower diastereoselectivity was obtained in the coupling. Interestingly, tris-TMSCp complex 5c and SmCp<sub>2</sub> 5d proved unreactive. This is likely due to the steric hindrance associated with 5c and the lower reducing ability of 5d. Switching to the bulkier DPMSCp ligands in 5e (DPMS = diphenylmethylsilyl) gave anti-1a with very good regiocontrol (91:9) and diastereocontrol (92:8 dr). Bulkier TPSCp ligands in 5f gave anti-1a with lower diastereocontrol (TPS = triphenylsilyl). The ability to isolate



Scheme 3 Proposed mechanism and origin of regio- and diastereocontrol in the  $SmCp^{R}_{2}$ -mediated coupling of **2a** and **3a**. R = (CH<sub>2</sub>)<sub>3</sub>CO<sub>2</sub>Et.



Fig. 1 X-ray characterisation of  $\text{SmCp}_2^R$  reagents including novel complexes **5c**, **5e** and **5f**.

and characterise  $\text{SmCp}_{2}^{\text{R}}$  reagents by X-ray crystallography, and thus understand the environment around the Sm(II) centre, is an advantage when tailoring their properties (Fig. 1). Complexes **5e** and **5f** are the first SmCp<sub>2</sub><sup>R</sup> systems bearing monosubstituted Cp ligands to be structurally characterised by X-ray crystallography.<sup>14,15</sup>

The scope of the SmCp<sup>R</sup><sub>2</sub>-mediated coupling was explored using various allyl ethers 2 and ketoesters 3 (Scheme 4). Using Sm(DPMSCp)<sub>2</sub>(THF) 5e, lactone adducts 1a-c and 1g-i were obtained with high diastereocontrol (up to 99:1) and high regiocontrol (up to 99:1) in good yield (81-92%). Little diastereocontrol was observed in the coupling of ethyl ketone 3d to give 1d. The reaction of methyl ketone 3e resulted in a reversal of the observed diastereoselectivity and the formation of syn-1e, lending support to the six-membered transition state proposed for the reaction, in which the larger ketone substituent preferentially adopts an equatorial orientation (cf. Scheme 3). No lactone product was observed when analogous phenyl ketone 3f was subjected to the cross-coupling procedure. Interestingly, the cross-coupling of (E)-((but-2-en-1-yloxy)methyl)benzene 2c with 3a, using 5e, gave lactone 1l as the major regioisomeric product. However, switching to the use of SmCp\*2THF2 5a allowed the opposite lactone regioisomer 1k to be obtained from the same combination of coupling partners. Thus, fine-tuning of SmCp<sup>R</sup><sub>2</sub> reagents allowed partners to be united in complementary fashion.  $SmCp_{2}^{*}(THF)_{2}$  5a was also found to be the optimal reagent for the cross-coupling of propargylic ether 2a' with keto esters 3 to give allenyl lactones 1m-r in good to excellent yields (52-93%) and excellent regiocontrol in all cases (99:1) (Scheme 5).

Interestingly, the coupling of allyl/propargyl ethers 2 and ketoesters 3 can be telescoped with our previously reported lactone radical cyclisations using SmI2-H2O to deliver decorated cycloheptanols 4. The versatility, selectivity, and mutual compatibility of Sm(II) reagents<sup>16</sup> is key to the success of this telescoped ET approach that converts simple substrates to complex products. For example coupling of allyl ether 2a and ketoesters 3a/c using SmCp<sup>R</sup><sub>2</sub> reagent 5e, followed by addition of SmI<sub>2</sub>-H<sub>2</sub>O (5 fold excess to ensure complete conversion) and in situ ester-alkene radical cyclisation (via transition structure I),<sup>17</sup> gave the desired 7-membered carbocycles 4a and 4b which were isolated as single diastereoisomers in good overall yield (Scheme 6).<sup>18</sup> The intermediate  $\delta$ -lactones **1a/c** are the most complicated substrates used to date in such radical cyclisations.<sup>17,18</sup> These radical cyclisations require ET to the ester carbonyl of complex  $\delta$ -lactones 1 – a process made possible by the mixing of SmI<sub>2</sub> in THF with H<sub>2</sub>O.<sup>17</sup> No cyclization was observed using SmCp<sup>R</sup><sub>2</sub>.<sup>11</sup> Pleasingly, the analogous



**Scheme 4** Investigating the scope of the coupling mediated by  $Sm(i)Cp_{2}^{P_{2}}$  reagents. <sup>a</sup> Diastereoselectivities, regioselectivities and yields (sum of diastereo-isomers) were determined by <sup>1</sup>H NMR using 1,2,4,5-tetrachloro-3-nitrobenzene as internal standard. Isolated yields in parentheses correspond to that of single regio- and diastereoisomers. <sup>b</sup>Cp\*<sub>2</sub>Sm(THF)<sub>2</sub> **5a** was used.

one pot process employing propargyl ether 2a' and 3a/c/j allowed both the chemo- and diastereoselectivity of the process to be switched: addition of Cp\*<sub>2</sub>Sm(THF)<sub>2</sub> 5a followed by SmI<sub>2</sub>-H<sub>2</sub>O (1.7 fold excess) triggered cross-coupling and an ester-allene radical cyclisation (*via* transition structure II)<sup>17,18</sup> and resulted in the formation of cycloheptan-1,4-diol products 4c, 4d and 4e, rather than hemiketal products, and with the opposite relative stereochemistry at the highlighted stereocentre.<sup>19</sup> Cycloheptanols 4c, 4d and 4e were isolated as single diastereoisomers in good to high overall yield. The two complementary processes result in the formation of four contiguous stereocenters and two new carbon– carbon bonds in one pot.

In summary, we have optimised an approach to substituted  $\delta$ -lactones that involves the regio- and diastereoselective coupling of allyl/propargyl ethers and ketoesters, mediated by SmCp<sup>R</sup><sub>2</sub>



**Scheme 5** Investigating the scope of the coupling mediated by  $Sm(II)Cp_{2}^{R_{2}}$  reagents. <sup>a</sup>Regioselectivities and yields were determined by <sup>1</sup>H NMR using 1,2,4,5-tetrachloro-3-nitrobenzene as internal standard. Isolated yields in parentheses correspond to that of single regioisomers.



Scheme 6 A telescoped approach to complex cycloheptanols from simple starting materials using two Sm(II) reagents.

reagents. Screening of the Cp ligands on Sm(n) was employed to achieve high regio and diastereocontrol in some cases. Crucially,  $SmI_2$  gave unsatisfactory results in the transformation. The process has been exploited in a telescoped approach to complex cycloheptanols in which two Sm(n) reagents act in turn on the simple starting materials.

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