Abstract: Treatment of γ- and δ-lactones having a sulfinyl group at the γ- and δ-positions with isopropylmagnesium chloride in THF at −78 °C gave γ-chloromagnesio γ-lactones and δ-chloromagnesio δ-lactones, respectively, by the sulfoxide–magnesium exchange reaction in high yields. Comparing the stability of the γ-chloromagnesio γ-lactones with that of the δ-chloromagnesio δ-lactones, the former was found to be much more stable. The reaction of these γ-chloromagnesio γ-lactones and δ-chloromagnesio δ-lactones with electrophiles and the stereochemistry of the reactions are discussed.

Key words: γ-chloromagnesio γ-lactone, δ-chloromagnesio δ-lactone, sulfoxide–magnesium exchange reaction, organomagnesium compound, Grignard reagent

Organomagnesium compounds, generally called as Grignard reagents, were discovered by V. Grignard over 100 years ago.1 Grignard reagents are easily prepared from alkyl- or aryl halides with magnesium metal in an ethereal solvent and are usually stable at room temperature and storable for a long period of time. In addition, Grignard reagent can act as a base and a nucleophile as well. These are the reasons why Grignard reagents have been one of the most important reagents for the formation of a carbon–carbon bond on reaction with carbonyl compounds or alkyl halides.2

Although Grignard reagents are less basic and less nucleophilic than the corresponding organolithium reagents, the carbon–magnesium bond is still highly reactive and it has long been generally recognized that the presence of electrophilic functional groups, such as esters, nitriles, and ketones, cannot be compatible with Grignard reagents. However, recently, the preparation of functionalized Grignard reagents and their properties have been studied and reported by Knochel3 and others. The functionalized Grignard reagents are those of functionalized arylmagnesium reagents,4 polyfunctional heteroarylmagnesium reagents,5 and functionalized alkenylmagnesium reagents.6 These functionalized magnesium reagents have ester, nitrile, halogen, and amide as the functional groups. However, these functional groups are usually present directly on the aromatic ring or on the sp²-carbon, which means that there is no acidic α-hydrogen, although some exception is also reported.7

In our previous studies, it was found that the reaction of alkyl aryl sulfoxides having a heteroatom at the carbon bearing the sulfinyl group, such as sulfinylloxiranes 1 (X = O) and sulfinylaziridines 1 (X = NAr), with alkylmetals (alkyllithiums and Grignard reagents) resulted in the formation of oxiranyl anions 2 (X = O)8,9 and aziridinyl anions 2 (X = NAr) (Scheme 1).5,10 Namely, the bond between the sulfur and the carbon bearing a heteroatom is cleaved by the reaction with alkylmetals through the sulfoxide–metal exchange reaction.11 Furthermore, we found that the oxiranyl anions and aziridinyl anions 2 reacted with several electrophiles to give epoxides and aziridines 3 in good yields.

In continuation of this chemistry, we envisaged that if Grignard reagents react with the sulfinyl group in lactones 4, γ-chloromagnesio γ-lactones 5 (n = 1) and δ-chloromagnesio δ-lactones 5 (n = 2) could be generated via sulfoxide–magnesium exchange reaction.11 We also anticipated that the further reaction of 5 with various electrophiles would afford lactones 6 having a carbon–carbon bond at the γ- and δ-position, respectively. We report here, in detail, the first example for the generation of γ-chloromagnesio γ-lactones and δ-chloromagnesio δ-lactones and the investigation of their properties and the reaction with electrophiles (Scheme 1).12

Scheme 1

Synthesis of γ-p-Tolylsulfanyl γ-Lactones and δ-p-Tolylsulfanyl δ-Lactones

At first, γ-(p-tolylsulfanyl) γ-lactones and δ-(p-tolylsulfanyl) δ-lactones 4 were synthesized as follows. Thus, 1-
chlorovinyl p-tolyl sulfoxide (7) was synthesized starting from methyl formate and chloromethyl p-tolyl sulfoxide in three steps in 75% overall yield (Scheme 2). Lithium enolate of tert-butyl 4-phenylbutyrate (4.5 equiv) was generated from tert-butyl 4-phenylbutyrate with LDA in THF at –78 °C and to this reaction mixture was added a solution of 7 in THF. The addition reaction was found to be instantaneous and the adduct 8 was obtained within one minute in 99% yield. When less amount of the lithium enolate of tert-butyl 4-phenylbutyrate was used, the reaction was not completed.

![Scheme 2](image)

Although adduct 8 has three chiral centers, only one isomer was obtained judging from its 1H NMR spectrum. Next, the adduct 8 was treated with trifluoroacetic anhydride (TFAA) in the presence of NaI in acetone at –50 °C to give γ-lactone 9 having a tolylsulfanyl group at the γ-position. The presumed mechanism of this reaction is shown in Scheme 2. First, the reaction of the sulfoxide 8 with TFAA gives an acyloxysulfonium ion. At the same time, the tert-butyl ester is eliminated by trifluoroacetic acid to carboxylic acid I. The iodine anion then attacks the chlorine atom to give thionium ion II. The oxygen of the carboxylic acid attacks intramolecularly the thionium ion to afford the γ-lactone 9. Two diastereomers were observed on silica gel TLC and they could be separated by silica gel column chromatography. In order to determine the stereochemistry of these two products 9a and 9b, NOESY spectra of the lactones were measured. From detailed inspection of the spectra, we were able to determine that the main lactone 9a has cis-stereochemistry as shown in Scheme 2.

In a similar way, the addition reaction of tert-butyl 4-phenylbutyrate with vinyl sulfoxide 7 was carried out and the intermediate of this addition reaction was trapped with iodomethane to give adduct 10 in 99% yield as a single isomer (Scheme 3).

![Scheme 3](image)

As the treatment of 10 with TFAA and NaI did not give the desired γ-lactone but a complex mixture, tert-butyl ester group was converted to the carboxylic acid with trifluoroacetic acid (TFA) in dichloromethane to give 11 in 91% yield. Carboxylic acid 11 was treated with TFAA and NaI in the same way as described above to afford a mixture of γ-lactones 12a (36%) and 12b (37%). The stereochemistry of 12a and 12b was again determined by NOESY spectra of both lactones. In a similar way, the intermediate of the addition reaction of 7 with lithium enolate of tert-butyl 4-phenylbutyrate was trapped with allyl iodide to give 13 in 85% yield. Removal of the tert-butyl ester group of 13 with TFA followed by the treatment with
TFAA-NaI gave a mixture of \( \gamma \)-lactones 14a and 14b having an allyl group at the \( \gamma \)-carbon in moderate yield. Next, the synthesis of \( \delta \)-sulfanyl \( \delta \)-lactones 18 was investigated (Scheme 4). Lithium enolate of tert-butyl 4-phenylbutyrate was generated from tert-butyl 4-phenylbutyrate with LDA in THF in the presence of HMPA and to this reaction mixture was added a solution of (3-iodo)propyl tolyl sulfide (15) in THF to afford the alkylated ester 16 in 82% yield. The sulfanyl group of 16 was oxidized with \( m \)-chloroperbenzoic acid (MCPBA) to a sulfanyl group, and the resulting sulfanyl ester was chlorinated with \( N \)-chlorosuccinimide (NCS). Finally, the tert-butyl ester was converted to the carboxylic acid 17 with TFA in 78% overall yield from 16. Carboxylic acid 17 was treated with TFAA in the presence of NaI in propionitrile at \(-50^\circ C\) to afford the desired \( \delta \)-sulfanyl \( \delta \)-lactone 18 in moderate yield.

**Scheme 4**

On a silica gel TLC, two products could be observed and they were separated by silica gel column chromatography as a less polar main product 18a (45%) and a more polar minor product 18b (22%). The stereochemistry of the two products was easily determined from the coupling pattern of the hydrogen at the carbon bearing the sulfanyl group as depicted in Scheme 4. Thus, the hydrogen of the minor product 18b showed a double-double-doublet at \( \delta = 5.55 \). The small coupling constant \( (J = 0.6 \text{ Hz}) \) indicated that the hydrogen has long-range coupling (long-range W coupling) \( ^3 \) between the equatorial hydrogen on the \( \beta \)-carbon (depicted in Scheme 4).

Generation of \( \gamma \)-Chloromagnesio \( \gamma \)-Lactones and \( \delta \)-Chloromagnesio \( \delta \)-Lactones from \( \gamma-p \)-Tolylsulfinyl \( \gamma \)-Lactones and \( \delta \)-Tolylsulfinyl \( \delta \)-Lactones, Respectively, with \( i \)-PrMgCl

Generation of \( \gamma \)-chloromagnesio \( \gamma \)-lactones and \( \delta \)-chloromagnesio \( \delta \)-lactones was investigated next. At first, 9a and 18a were used in the following studies. Sulfide 9a was oxidized with MCPBA at \(-50^\circ C\) to afford sulfoxide 19a as a mixture of two diastereomers in high yield. Next, the mixture of the sulfoxides 19a was treated with 1.6 equivalents of \( i \)-PrMgCl at \(-78^\circ C\) for 10 minutes (a solution of 19a in THF was added to a solution of \( i \)-PrMgCl in THF) to give the desulfynylated product 21 in 94% yield via sulfoxide–magnesium exchange reaction without a trace of the starting sulfoxide 19a. Quenching this reaction with MeOD gave deuterated product (deuterated at \( \gamma \)-position) 21 with 99% deuterium incorporation. This result showed that the intermediate of this reaction was \( \gamma \)-chloromagnesio \( \gamma \)-lactone 20 (see Scheme 5).

In a similar way, sulfoxide–magnesium exchange reaction of \( \delta \)-tolylsulfinyl \( \delta \)-lactone 22a, which was synthesized from \( \delta \)-tolylsulfinyl \( \delta \)-lactone 18a with MCPBA in a quantitative yield, was carried out with three equivalents of \( i \)-PrMgCl and the reaction was quenched with MeOD to give \( \delta \)-lactone 24 deuterated at \( \delta \)-position in 87% yield (D-content 99%). When less than three equivalents of \( i \)-PrMgCl was used in this reaction, the sulfoxide-magnesium exchange reaction did not go to completion. Obviously, the intermediate of this reaction was the \( \delta \)-chloromagnesio \( \delta \)-lactone 23. At this stage, we were worried about an intermolecular or an intramolecular proton abstraction of these magnesiated lactones; because, both 20 and 23 have relatively acidic hydrogen on the \( \alpha \)-position. However, no deuterium incorporation at the \( \alpha \)-position of 21 and 24 were observed as revealed by their \( ^1\text{H} \) NMR spectra.

Next, the stability of \( \gamma \)-chloromagnesio \( \gamma \)-lactone 20 and \( \delta \)-chloromagnesio \( \delta \)-lactone 23 was investigated. The stability of 20 and 23 was evaluated by the chemical yield and the rate of deuterium incorporation of the reaction of 19a and 22a with \( i \)-PrMgCl followed by MeOD and the results are summarized in Table 1. The result of the reaction of 19a already mentioned in Scheme 5 is described in entry 1. The result of the reaction of 19a with \( i \)-PrMgCl at \(-78^\circ C\) for 1 hour is shown in entry 2. Comparing the results shown in entries 1 and 2, it is expected that the generated \( \gamma \)-chloromagnesio \( \gamma \)-lactone 20 is stable at \(-78^\circ C\) for over one hour. Other reaction conditions for the reaction of 19a with \( i \)-PrMgCl are shown in entries 3 to 6.
These data indicate that γ-chloromagnesio γ-lactone 20 is rather stable even at about −50 °C.

Contrary to the results described above, δ-chloromagnesio δ-lactone 23 generated from δ-p-tolylsulfanyl δ-lactone 22a with i-PrMgCl was found to be fairly unstable. Thus, the reaction of 22a carried out even at −78 °C for 10 minutes produced 24 in only 87% yield with several unknown by-products (entry 1). When the reaction mixture was stirred at −78 °C for one hour, the yield of 24 was markedly diminished (entry 2). When the temperature of the reaction mixture was allowed to warm to −50 °C, we obtained only a complex mixture (entry 4). We still find it difficult to propose a rational reason for the instability of δ-chloromagnesio δ-lactone 23 compared to 20 – the size of the ring is one possibility.

In a similar way, the sulfanyl group of 12a was oxidized with MCPBA to a sulfinyl group, and the resultant sulfinyl lactone was treated with 1.6 equivalents of i-PrMgCl to give lactone 26 bearing a methyl group at the γ-position via γ-chloromagnesio γ-lactone 25 in 71% overall yield. When the reaction was quenched with MeOD, the rate of deuterium incorporation at the γ-position was 99%. Next, γ-sulfinyl γ-lactone 14a was converted to γ-lactone bearing an allyl group 28 with 99% deuterium incorporation via γ-chloromagnesio γ-lactone 27 in 82% overall yield. Interestingly, although both γ-lactones 26 and 28 have two stereogenic centers, only a single product was obtained. No isomer was observed from detailed inspection of their 1H NMR spectra. From these results, it was found that the stereochemistry of the carbon bearing the sulfinyl group of 12a or 14a at the γ-position was retained throughout the whole sequence (see Scheme 6).10,16

In order to extend this unprecedented Grignard reagent as a new synthetic method for γ-substituted γ-lactones, trapping of γ-chloromagnesio γ-lactones 20 and 31 with several electrophiles was investigated (Scheme 7). Thus, the reaction of 19a and 19b with i-PrMgCl followed by ethyl chloroformate at −78 °C for one hour gave good yields of esters 29 and 32. Interestingly, both products, 29 and 32, were obtained each as a single diastereomer.
Configuration of the products was again confirmed by NOESY experiments and the reactions were found to be highly stereospecific as shown in Scheme 7. Namely, the stereochemistry of the anionic carbon was retained throughout the sequence. The reactions of 20 and 31 with benzoyl chloride at −78 °C for one hour gave products 30 and 33 in 54 and 65% yield, respectively, as a single product. When this reaction mixture was slowly allowed to warm to −50 °C and further stirred at −50 °C for one hour, the result was almost the same compared with the condition described above. No isomer was observed from detailed inspection of their 1H NMR spectra.

In order to investigate the generality of these reactions, 34a and 34b were used in the following studies (Scheme 8). Treatment of γ-tolylsulfinyl γ-lactones 34a and 34b with i-PrMgCl followed by benzoyl chloride in the same way as described above resulted in the formation of γ-lactones 35 and 36, respectively, via γ-chloromagnesio γ-lactones, again highly stereospecifically in moderate yields.

In order to compare the reactivity of δ-chloromagnesio δ-lactones with γ-chloromagnesio γ-lactones, we tried to trap δ-chloromagnesio δ-lactones generated from 22a and 22b with ethyl chloroformate as an electrophile. In the same way described above, the reaction of 22a and 22b with i-PrMgCl followed by ethyl chloroformate at −78 °C for one hour gave the desired δ-lactones 37 and 38, respectively, however, the yields were miserably low (Scheme 7).

### Table 1

<table>
<thead>
<tr>
<th>Entry</th>
<th>Conditions</th>
<th>21 Yield (%)/D-content (%)</th>
<th>24 Yield (%)/D-content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>–78 °C, 10 min</td>
<td>94/99</td>
<td>87/99</td>
</tr>
<tr>
<td>2</td>
<td>–78 °C, 1 h</td>
<td>91/94</td>
<td>62/99</td>
</tr>
<tr>
<td>3</td>
<td>–78 °C, 2 h</td>
<td>85/91</td>
<td>55/99</td>
</tr>
<tr>
<td>4</td>
<td>–78 to −50 °C, 50 min, then −50 °C for 1 h</td>
<td>80/91</td>
<td>complex mixture</td>
</tr>
<tr>
<td>5</td>
<td>–78 to −50 °C, 50 min, then −50 °C for 2 h</td>
<td>80/88</td>
<td>–</td>
</tr>
<tr>
<td>6</td>
<td>–78 to −30 °C, 90 min, then −30 °C for 10 min</td>
<td>63/93</td>
<td>–</td>
</tr>
</tbody>
</table>

*a* Amount of i-PrMgCl used = 1.6 equiv.

*b* Amount of i-PrMgCl = 3.0 equiv.

*c* The results are described in Scheme 5.
Table 2.

| Tones | Magnesium reactive at the low temperature. Instability of results, action gave magnesio 1.6 equivalents of 1, 6, and 10). These results indicate that γ-chloromagnesio-γ-lactones 40a, 40c, and 40d were generated from the corresponding sulfoxides by the sulfioxide–magnesium exchange reaction, and these are stable at −78 °C for at least 10 minutes. Entries 6 to 8 show that γ-chloromagnesio-γ-lactone 40c is fairly stable even at −50 °C for at least one hour.

The reaction of γ-chloromagnesio-γ-lactones 40a and 40b with ethyl chloroformate at −78 °C for one hour gave the products 41b and 41d having an ethoxycarbonyl group in 36 and 46% yield, respectively (entries 2 and 4). In the same manner, the reaction of γ-chloromagnesio-γ-lactones 40a and 40b, derived from 39a and 39b, with benzoyl chloride gave γ-lactones having a benzoyl group at the γ-position, 41c and 41e, in up to 61% yield (entries 3 and 5). The yields of both reactions were not satisfactory and steric hindrance was thought to be the reason for the low yield. Interestingly, the products were obtained as a single diastereomer, and again the reaction proceeded in a highly stereospecific manner.

Entries 6–11 show the results concerning the γ-chloromagnesio-γ-lactones, 40c and 40d, generated from β,β-disubstituted γ-lactones 39c and 39d, respectively. As shown in the results in entries 6–8, and as already mentioned above, the γ-chloromagnesio-γ-lactones 40c generated from β,β-disubstituted γ-lactone 39c were found to be stable at below −50 °C. The reactivity of the γ-chloromagnesio-γ-lactone generated from 39c and 39d was investigated; however, both ethyl chloroformate and benzoyl chloride did not react at all with the generated γ-chloromagnesio-γ-lactones 40c and 40d. Steric hindrance (neopentyl position) was thought to be the reason for the low reactivity with the electrophiles.

In conclusion, we were able to generate, for the first time, γ-chloromagnesio-γ-lactones and δ-chloromagnesio-δ-lactones from γ-lactones and δ-lactones having a tolylsulfinyl group at the γ- or δ-position by the sulfoxide–magnesium exchange reaction. Comparing the stability of γ-chloromagnesio-γ-lactones with δ-chloromagnesio-δ-lactones, the former was found to be much more stable at low temperature and more reactive with some electrophiles. The presented procedure contributes to the synthesis of γ- or δ-lactones having multi-substituents.

All melting points were measured on Yanaco MP-S3 apparatus and are uncorrected. "H NMR spectra were measured in CDCl3 using Jeol JNMLA 500 and Burker XWIN-600 spectrometers. Electron–impact mass spectra (MS) were obtained at 70 eV by direct insertion on a HITACHI M-80B mass spectrometer. IR spectra were recorded on a Perkin-Elmer Spectrum One FT-IR instrument. Silica gel 60N (Kanto Chemical) containing 0.5% fluorescence reagent 254 and a quartz column were used for column chromatography and the products having UV absorption were detected by UV irradiation. In experiments requiring an anhydrous reagent, CH2Cl2, DIPA, Et3N, and pyridine were distilled from CaH2. THF was distilled from CaSO4 and distilled before use. Benzoyl chloride and ethyl chloroformate were distilled prior to use.

tert-Butyl 4-Chloro-2-(2-phenylethyl)-4-<p-tolylsulfinyl)butyrate (8)

tert-Butyl 4-phenylbutyrate (440 mg, 2.0 mmol) was added to a solution of LDA [2.0 mmol, prepared from i-Pr2NH (0.28 mL) and n-BuLi (1.25 mL, 1.6 M in hexane)] in anhyd THF (11.5 mL) at

9) while, about 50% of protonated lactone at the δ-position was observed from "H NMR spectrum. From these results, γ-chloromagnesio-γ-lactones were found to be more reactive at the low temperature. Instability of δ-chloromagnesio-δ-lactones is one explanation for the low yields of the products 37 and 38.

Finally, we investigated this reaction with β-monosubstituted γ-lactones 39a and 39b, and β,β-disubstituted γ-lactones, 39c and 39d, and the results are summarized in Table 2. γ-Sulfinylated γ-lactones 39 were treated with 1.6 equivalents of i-PrMgCl at −78 °C to give γ-chloromagnesio-γ-lactones 40 in quantitative yields, which was confirmed by quenching the reaction with MeOD. The reaction gave γ-deuterated γ-lactones 41 in almost quantitative yields with 95–99% deuterium incorporation (entries 1, 6, and 10). These results indicates that γ-chloromagnesio-γ-lactones 40a, 40c, and 40d were generated from the corresponding sulfoxides by the sulfioxide–magnesium exchange reaction, and these are stable at −78 °C for at

\[ \text{Scheme 8} \]

\[ \text{Scheme 9} \]
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**Table 2** Generation of γ-Chloromagnesio γ-Lactone 40 from 39 and Quenching with Electrophiles

<table>
<thead>
<tr>
<th>Entry</th>
<th>39</th>
<th>R&lt;sup&gt;1&lt;/sup&gt;</th>
<th>R&lt;sup&gt;2&lt;/sup&gt;</th>
<th>Electrophile</th>
<th>Conditions</th>
<th>41 Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>39a</td>
<td>Ph(CH&lt;sub&gt;2&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt;</td>
<td>H</td>
<td>MeOD</td>
<td>–78 °C, 10 min</td>
<td>41a 95 (D-content, 98%)</td>
</tr>
<tr>
<td>2</td>
<td>39a</td>
<td>Ph(CH&lt;sub&gt;2&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt;</td>
<td>H</td>
<td>ClCO&lt;sub&gt;2&lt;/sub&gt;Et</td>
<td>–78 °C, 1 h</td>
<td>41b 36&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>3</td>
<td>39a</td>
<td>Ph(CH&lt;sub&gt;2&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt;</td>
<td>H</td>
<td>PhCOCl</td>
<td>–78 °C, 1 h</td>
<td>41c 36&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>4</td>
<td>39b</td>
<td>Me(CH&lt;sub&gt;3&lt;/sub&gt;)&lt;sub&gt;5&lt;/sub&gt;</td>
<td>H</td>
<td>ClCO&lt;sub&gt;2&lt;/sub&gt;Et</td>
<td>–78 °C, 1 h</td>
<td>41d 46&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>5</td>
<td>39b</td>
<td>Me(CH&lt;sub&gt;3&lt;/sub&gt;)&lt;sub&gt;5&lt;/sub&gt;</td>
<td>H</td>
<td>PhCOCl</td>
<td>–78 °C, 1 h</td>
<td>41e 61&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>6</td>
<td>39c</td>
<td>(CH&lt;sub&gt;2&lt;/sub&gt;)&lt;sub&gt;14&lt;/sub&gt;-</td>
<td>H</td>
<td>MeOD</td>
<td>–78 °C, 10 min</td>
<td>41f 99 (D-content, 95%)</td>
</tr>
<tr>
<td>7</td>
<td>39c</td>
<td>(CH&lt;sub&gt;2&lt;/sub&gt;)&lt;sub&gt;14&lt;/sub&gt;-</td>
<td>H</td>
<td>MeOD</td>
<td>–78 °C, 1 h</td>
<td>41f 90 (D-content, 91%)</td>
</tr>
<tr>
<td>8</td>
<td>39c</td>
<td>(CH&lt;sub&gt;2&lt;/sub&gt;)&lt;sub&gt;14&lt;/sub&gt;-</td>
<td>H</td>
<td>MeOD</td>
<td>–78 to –50 °C, 1 h</td>
<td>41f 85 (D-content, 94%)</td>
</tr>
<tr>
<td>9</td>
<td>39c</td>
<td>(CH&lt;sub&gt;2&lt;/sub&gt;)&lt;sub&gt;14&lt;/sub&gt;-</td>
<td>H</td>
<td>ClCO&lt;sub&gt;2&lt;/sub&gt;Et</td>
<td>–78 °C, 1 h</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>39d</td>
<td>4-MeOC&lt;sub&gt;6&lt;/sub&gt;H&lt;sub&gt;4&lt;/sub&gt;(CH&lt;sub&gt;2&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Me</td>
<td>MeOD</td>
<td>–78 °C, 10 min</td>
<td>41g 99 (D-content, 99%)</td>
</tr>
<tr>
<td>11</td>
<td>39d</td>
<td>4-MeOC&lt;sub&gt;6&lt;/sub&gt;H&lt;sub&gt;4&lt;/sub&gt;(CH&lt;sub&gt;2&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Me</td>
<td>ClCO&lt;sub&gt;2&lt;/sub&gt;Et</td>
<td>–78 °C, 1 h</td>
<td>0</td>
</tr>
</tbody>
</table>

<sup>a</sup>The main isomer of the γ-lactone having a p-tolylsulfinyl group at the γ-position was used.

<sup>b</sup>Some amount of lactone was contaminated and the yield was determined from its 1H NMR spectrum.

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γ-Sulfanyl γ-Lactones; 3-(2-Phenylethyl)-5-(p-tolylsulfonyl)dihydrofuran-2-ones (9a,b); Typical Procedure

A solution of NaI (356 mg, 2.4 mmol) in anhyd acetone (14 mL) was stirred for 15 min at –55 °C. TFAA (0.34 mL, 2.4 mmol) was added dropwise to the solution of NaI with stirring at –55 °C and the mixture was stirred for 15 min. A solution of the adduct 8 (200 mg, 0.48 mmol) in anhyd acetone (2 mL) was added dropwise to the solution of NaI and TFAA at –55 °C with stirring and the reaction mixture was stirred for 10 min. The reaction was quenched by adding sat. aq NaHCO<sub>3</sub> (20 mL) followed by sat. aq Na<sub>2</sub>SO<sub>3</sub> (5 mL) and the mixture was extracted with CHCl<sub>3</sub> (3 × 30 mL). The organic layer was washed with sat. aq NaHCO<sub>3</sub> (30 mL) and dried (MgSO<sub>4</sub>). Filtration and evaporation of the solvent gave a residue which was purified by silica gel column chromatography (hexane–EtOAc, 10:1) to afford 9a (78 mg, 52%) and 9b (46.5 mg, 31%) as colorless crystals.

9a
Mp 70–71 °C (hexane).

IR (KBr): 2919, 1772 (C=O), 1492, 1455, 1170, 923 cm<sup>–1</sup>.

1H NMR: δ = 1.62–1.71 (m, 1 H), 1.84 (dt, J = 13.2, 9.3 Hz, 1 H), 2.14–2.23 (m, 1 H), 2.32 (s, 3 H), 2.51–2.75 (m, 4 H), 5.56 (dd, J = 11.0, 2.7 Hz, 1 H).
**Adduct of an Ester Having Functional Groups at the γ-Position:**

**tert-Butyl 4-Chloro-2-(2-phenylthio)-4-(p-tolylsulfanyl)pentanoate (10): Typical Procedure**

tert-Butyl 4-phenylbutyrate (440 mg, 2 mmol) was added to a solution of LDA [2.0 mmol; prepared from i-Pr₃N (0.28 mL) and n-Buti (1.25 mL, 1.6 M in hexane)] in anhyd THF (12 mL) at −78 °C with stirring. The mixture was stirred for 15 min, then a solution of 7 (100 mg, 0.5 mmol) in anhyd THF (1 mL) was added. The mixture was stirred for 5 min at −78 °C. Mel (354 mg, 2.5 mmol) was added and the mixture was stirred for 5 min. The reaction was quenched by adding sat. aq NH₄Cl (30 mL) and the mixture was extracted with CHCl₃ (3 × 30 mL). The combined organic layers were dried (MgSO₄), filtered, and the filtrate was evaporated to give a residue which was purified by gel column chromatography (hexane–EtOAc, 10:1) to afford 10 (208 mg, 99%) as colorless crystals.

Mp 85–86 °C (hexane).

IR (KBr): 2937, 2927, 1722 (C=O), 1494, 1457, 1391, 1366, 1144, 1051 (S=O) cm⁻¹.

1H NMR: δ = 1.45 (d, J = 9.0 Hz, 3 H), 1.48 (s, 9 H), 1.58 (m, 1 H), 1.79–2.18 (m, 4 H), 2.43 (s, 3 H), 2.55–2.68 (m, 3 H), 2.77–2.84 (m, 1 H), 7.15–7.33 (m, 7 H), 7.59–7.63 (m, 2 H).

Anal Calcd for C₂₀H₂₂S₂O₃S: C, 67.63; H, 7.18; Cl, 8.15; S, 7.37. Found: C, 66.14; H, 7.09; Cl, 8.09; S, 7.42.

**4-Chloro-2-(2-phenylthio)-4-(p-tolylsulfanyl)pentanoic Acid (11)**

Trifluoroacetic acid (TFA, 0.56 mL, 7.5 mmol) was added to a solution of 10 (208 mg, 0.5 mmol) in CH₂Cl₂ (10 mL) at r.t. The reaction mixture was stirred for 1 d and the reaction was quenched by adding sat. aq NaHCO₃ (20 mL). The mixture was extracted with CH₂Cl₂ (3 × 20 mL) and the aqueous separated. The aqueous layer was acidified with aq 10% HCl and extracted with CH₂Cl₂ (3 × 20 mL). The combined organic layers were evaporated to give 11 (172 mg, 91%) as colorless crystals.

Mp 93–94 °C (EtOAc–hexane).

IR (KBr): 2923, 1732 (C=O), 1454, 1032 (S=O), 811 cm⁻¹.

1H NMR: δ = 1.45 (s, 3 H), 1.90–1.99 (m, 1 H), 2.02–2.12 (m, 1 H), 2.31 (dd, J = 15.0, 2.1 Hz, 1 H), 2.43 (s, 3 H), 2.93–2.99 (m, 1 H), 2.69–2.75 (m, 3 H), 7.17–7.29 (m, 5 H), 7.31 (d, J = 8.2 Hz, 2 H), 7.62 (d, J = 8.2 Hz, 2 H).

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tert-Butyl 2-(2-Phenylethyl)-5-(p-tolylsulfinyl)pentanoate (16)

tert-Butyl 4-phenylbutyrate (754 mg, 3.42 mmol) was added to a solution of LDA (3.42 mmol, prepared from i-Pr,NH2 (0.48 mL and n-BuLi (2.14 mL), 1.6 M in hexane)) in the presence of HMPA (0.6 mL, 3.42 mmol) in anhyd THF (4.8 mL) at −78 °C with stirring. The mixture was stirred for 10 min, then a solution of 3-(p-tolylsulfinyl)propyl iodide (200 mg, 0.68 mmol) in THF (2 mL) was added. The reaction mixture was stirred at −78 °C for 10 min. The reaction was quenched by adding sat. aq NH₄Cl (30 mL) and the mixture was extracted with CHCl₃ (3 × 30 mL). The combined organic layers were washed with sat. aq NH₄Cl (30 mL) and dried (MgSO₄). Filtration and evaporation of the solvent gave a residue which was purified by silica gel column chromatography (hexane–EtOAc, 10:1) to afford 16 (217 mg, 82%) as colorless oil.

IR ( neat): 2930, 1724 (C=O) (Cₐ₅OAc), 1499, 1366, 1145 cm⁻¹.

1H NMR: δ = 1.43 (s, 9 H), 1.57–1.63 (m, 3 H), 1.64–1.72 (m, 2 H), 1.85–1.93 (m, 1 H), 2.25 (sept. 1 H), 2.54–2.64 (m, 2 H), 2.84 (t, J = 6.7 Hz, 2 H), 7.08 (d, J = 7.9 Hz, 2 H), 7.14–7.19 (m, 3 H), 7.23 (d, J = 8.7 Hz, 2 H), 7.28 (d, J = 7.4 Hz, 2 H).

MS: m/z (%): 218 (M⁺, 65), 328 (100), 311 (15), 280 (14), 219 (7), 205 (23), 187 (15), 163 (25), 137 (28), 124 (44), 91 (60), 57 (28).

HRMS: m/z calcd for C₂₉H₂₈O₃S (M⁺): 384.2123; found: 384.2132.

5-Chloro-2-(2-phenylethyl)-5-(p-tolylsulfinyl)pentanoic Acid (17)

MCPBA (206 mg) was added to a solution of 16 (218 mg, 0.776 mmol) in CHCl₃ (11 mL) at 0 °C with stirring. The solution was stirred for 10 min, and the reaction was quenched by adding sat. NaHCO₃ (20 mL). The mixture was extracted with CHCl₃ (3 × 30 mL) and the combined organic layers were washed with sat. aq NaHCO₃ (60 mL) and dried (MgSO₄). Filtration and evaporation of the solvent gave a residue which was purified by silica gel column chromatography to give 18a (308 mg, 92%) as a colorless oil.

IR (KBr): 3027, 2954, 2926, 2869, 1713 (C=O), 1492, 1454, 1374, 1169, 1070, 1017, 814 cm⁻¹.

1H NMR: δ = 1.59–1.66 (m, 1 H), 1.75–1.82 (m, 1 H), 1.85–1.92 (m, 1 H), 2.09–2.20 (m, 1 H), 2.23–2.38 (m, 3 H), 2.64–2.77 (m, 2 H), 5.58 (dd, J = 8.4, 4.2 Hz, 1 H), 7.13 (d, J = 7.8 Hz, 2 H), 7.18 (m, 3 H), 7.27 (d, J = 7.8 Hz, 2 H), 7.41 (d, J = 8.4 Hz, 2 H).

Anal. Calcd for C₂₉H₂₈O₃S: C, 73.58; H, 6.79; S, 9.82. Found: C, 73.54; H, 6.71; S, 9.73.

5-Chloro-2-(2-phenylethyl)-5-(p-tolylsulfinyl)dihydrofuran-2-ones (19a,b)

MCPBA (42.3 mg; 0.18 mmol) was added to a solution of 9a (50 mg, 0.16 mmol) in CHCl₃ (5 mL) at 0 °C with stirring. The mixture was stirred for 30 min and the reaction was quenched by adding sat. NaHCO₃ (50 mL) and NaHCO₃ (30 mL). The mixture was extracted with CHCl₃ (3 x 20 mL) and the combined organic layers were washed with sat. aq NaHCO₃ (60 mL) and dried (MgSO₄). Filtration and evaporation of the solvent gave a residue which was purified by silica gel column chromatography (hexane–EtOAc, 10:1) to afford 19a (49.4 mg, 94%) as a 9:1 mixture of two diastereomers.

19a

Colorless crystals; mp 117–120 °C (EtOAc).

IR (KBr): 2950, 2919, 1784 (C=O), 1770 (C=O), 1494, 1455, 1303, 1208, 1156, 1089, 1059 (S=O), 1034, 805 cm⁻¹.

1H NMR: δ = 1.24–1.37 (m, 1 H), 1.94–2.01 (m, 1 H), 2.09–2.18 (m, 1 H), 2.39 (s, 3 H), 2.48–2.90 (m, 4 H), 4.92 (tt, J = 9.5 Hz, 0.9 Hz, 5.18 (t, J = 10.0 Hz, 0.1 H), 7.11–7.36 (m, 5 H), 7.35, 7.40 (d, J = 8.0 Hz, 2 H each).

MS: m/z (%): 329 ([M + 1]⁺, trace), 312 (58), 189 (68), 171 (23), 140 (25), 117 (26), 91 (100), 84 (15).

HRMS: m/z calcd for C₉H₁₄O₂S (M⁺): 329.1201; found: 329.1209.


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Anal. Calcd for C$_{20}$H$_{22}$O$_3$S: C, 70.15; H, 6.48; S, 9.36. Found: C, 70.18; H, 6.47; S, 9.35.

Generation of γ-Chloromagnesio γ-Lactones and δ-Chloromagnesio δ-Lactones; 5-Deuterio-3-(2-phenylethyl)dihydrofuran-2-one (21); Typical Procedure

A solution of i-PrMgCl (2.0 mol/L, 0.07 mL) in THF was added to a solution of 19a (30 mg, 0.09 mmol) in THF (6 mL) in a flame-dried flask at −78 °C under argon. The reaction mixture was stirred for 10 min, quenched with MeOD (3 mL), and extracted with CHCl$_3$ (3 × 20 mL). The combined organic layers were dried (MgSO$_4$), filtered, and the solvent was evaporated to give a residue which was purified by silica gel column chromatography (hexane–EtOAc, 5:1) to afford 21 (16.1 mg, 94%) as a colorless oil.

IR (neat): 3029, 2939, 1782 (C=O), 1753 (C=O), 1497, 1454, 1378, 1244, 1143, 1108 cm$^{-1}$.

MS: m/z (%) = 262 (M$^+$, 17), 189 (31), 171 (7), 158 (58), 140 (10), 129 (8), 112 (100), 105 (26), 91 (85), 77 (7).

HRMS: m/z calcld for C$_{15}$H$_{18}$O$_4$ (M$^+$): 262.1204; found: 262.1208.

5-Deuterio-3-(2-phenylethyl)dihydrofuran-2-one (24) Colorless oil.

IR (neat): 2934, 1732 (C=O), 1454, 1375, 1250, 1144, 1094, 751 cm$^{-1}$.

1H NMR: δ = 1.55–1.63 (m, 1 H), 1.74–1.81 (m, 1 H), 1.83–1.96 (m, 2 H), 2.13 (s, J = 7.3 Hz, 1 H), 2.24–2.29 (m, 1 H), 2.43–2.47 (m, 1 H), 2.69–2.79 (m, 2 H), 4.26–4.30 (m, 1 H), 7.18–7.21 (m, 3 H), 7.26–7.30 (m, 2 H).

MS: m/z (%) = 205 (M$^+$, 4), 101 (100), 91 (42), 65 (11).

HRMS: m/z calcld for C$_{15}$H$_{18}$O$_2$ (M$^+$): 205.1212; found: 205.1210.

5-Deutero-5-methyl-3-(2-phenylethyl)dihydrofuran-2-one (26) Colorless oil.

IR (neat): 2973, 2930, 1763 (C=O), 1496, 1454, 1244, 1143, 1108, 976 cm$^{-1}$.

1H NMR: δ = 1.34 (s, 3 H), 1.71–1.83 (m, 1 H), 1.97–2.24 (m, 3 H), 2.57–2.83 (m, 3 H), 7.19–7.32 (m, 5 H).

MS: m/z (%) = 204 (M$^+$, 10), 100 (100), 91 (35), 65 (8), 41 (8).

HRMS: m/z calcld for C$_{16}$H$_{18}$O$_2$ (M$^+$): 204.1150; found: 204.1155.

5-Allyl-5-deutero-3-(2-phenylethyl)dihydrofuran-2-one (28) Colorless oil.

IR (neat): 2925, 1770 (C=O), 1643, 1454, 1206, 975 cm$^{-1}$.

1H NMR: δ = 1.53–1.62 (m, 1 H), 1.68–1.80 (m, 1 H), 2.27 (dddd, J = 13.7, 9.2, 7.2, 4.9 Hz, 1 H), 2.36–2.83 (m, 6 H), 5.13–5.20 (m, 2 H), 5.71–5.85 (m, 1 H), 7.18–7.32 (m, 5 H).

MS: m/z (%) = 231 (M$^+$, 15), 190 (26), 172 (8), 144 (8), 127 (33), 109 (35), 91 (100), 77 (9).

HRMS: m/z calcld for C$_{16}$H$_{18}$O$_2$ (M$^+$): 231.1369; found: 231.1370.

5-Ethoxycarbonyl-3-(2-phenylethyl)dihydrofuran-2-ones (29 and 32)

A solution of i-PrMgCl (2.0 mol/L, 0.11 mL) in THF was added to a solution of 19a (45.4 mg, 0.14 mmol) in THF (5 mL) in a flame-dried flask at −78 °C under argon. After stirring the reaction mixture for 10 min, ethyl chloroformate (0.05 mL, 0.56 mmol) was added. The mixture was stirred for 1 h at −78 °C and the reaction was quenched by adding sat. aq NH$_4$Cl (20 mL). The mixture was extracted with CHCl$_3$ (3 × 20 mL) and the combined organic layers were dried (MgSO$_4$). Filtration and evaporation of the solvent gave a residue which was purified by silica gel column chromatography (hexane–EtOAc, 5:1) to afford 29 (23.1 mg, 63%) as a colorless oil.

IR (neat): 3029, 2939, 1782 (C=O), 1753 (C=O), 1497, 1454, 1378, 1217, 1155, 1070, 956 cm$^{-1}$.

1H NMR: δ = 1.32 (t, J = 7.1 Hz, 3 H), 1.71–1.83 (m, 1 H), 2.00 (dt, J = 12.8, 9.2 Hz, 1 H), 2.24–2.31 (m, 1 H), 2.54–2.61 (m, 1 H), 2.67–2.73 (m, 2 H), 2.79–2.84 (m, 1 H), 4.27 (q, J = 7.3 Hz, 2 H), 4.77 (dd, J = 9.2, 7.3 Hz, 1 H), 7.18–7.23 (m, 3 H), 7.28–7.31 (m, 2 H).

MS: m/z (%) = 262 (M$^+$, 17), 189 (31), 171 (7), 158 (58), 140 (10), 129 (8), 112 (100), 105 (26), 91 (85), 77 (7).

HRMS: m/z calcld for C$_{16}$H$_{18}$O$_2$ (M$^+$): 262.1204; found: 262.1208.

32 Colorless oil.

IR (neat): 2983, 2939, 1779 (C=O), 1746 (C=O), 1497, 1455, 1377, 1195, 1164, 1136, 1061, 1025, 937 cm$^{-1}$.

1H NMR: δ = 1.29 (t, J = 7.2 Hz, 3 H), 1.70–1.80 (m, 1 H), 2.19–2.29 (m, 2 H), 2.44–2.50 (m, 1 H), 2.62–2.77 (m, 3 H), 4.24 (q, J = 3.2 Hz, 2 H), 4.88 (dd, J = 9.2, 2.4 Hz, 1 H), 7.18–7.31 (m, 5 H).
5-Benzoyl-3-(2-phenylethyl)dihydrofuran-2-ones (30 and 33)

A solution of i-PrMgCl (2.0 mol/L, 0.11 mL) in THF (5 mL) was added to a solution of 19a (45.4 mg, 0.14 mmol) in THF (1 mL) in a flame-dried flask at –78 °C under argon. After stirring the reaction mixture for 10 min, benzoyl chloride (0.06 mL, 0.56 mmol) was added. The mixture was stirred for 1 h at –78 °C and the reaction mixture was quenched by adding sat. aq NH4Cl (20 mL). The mixture was extracted with CHCl3 (3 × 20 mL) and the combined organic layers were dried (MgSO4). Filtration and evaporation of the solvent gave a residue which was purified by silica gel column chromatography (hexane–EtOAc, 5:1) to afford 30 (22.3 mg, 54%) as colorless crystals.

30

Mp 87–88 °C (hexane).

IR (KBr): 2926, 1778 (C=O), 1694 (C=O), 1597, 1450, 1233, 1159 cm–1.

31

1H NMR: δ = 1.75–1.85 (m, 1 H), 2.16–2.31 (m, 2 H), 2.64–2.86 (m, 4 H), 5.26 (dd, J = 8.9, 7.0 Hz, 1 H), 7.16–7.32 (m, 5 H), 7.51 (t, J = 7.8 Hz, 2 H), 7.64 (J = 7.8 Hz, 1 H), 7.99 (J = 7.8 Hz, 2 H).

MS: m/z (%) = 294 (M+, 9%), 190 (25), 171 (12), 162 (9), 145 (24), 133 (15), 117 (22), 105 (100), 91 (66), 77 (41), 65 (11).

HRMS: m/z calcd for C16H15O3S (M+): 294.1255; found: 294.1257.


5-Benzoyl-3-methylidihydrofuran-2-ones (35 and 36)

35

Colorless crystals; mp 63–64 °C (hexane).

IR (KBr): 2976, 1785 (C=O), 1695 (C=O), 1591, 1451, 1222, 1167, 1007, 908 cm–1.

1H NMR: δ = 1.31 (d, J = 6.8 Hz, 3 H), 2.22–2.32 (m, 1 H), 2.61–2.77 (m, 2 H), 5.77 (dd, J = 9.5, 1.5 Hz, 1 H), 7.52 (dd, J = 9.3, 7.5 Hz, 1 H), 7.59–7.64 (m, 1 H), 7.98 (dd, J = 8.3, 1.2 Hz, 2 H).

MS: m/z (%) = 204 (M+, trace), 105 (100), 99 (14), 77 (30), 71 (10).

HRMS: m/z calcd for C16H15O3S (M+): 204.0785; found: 204.0784.

Anal. Calcd for C16H15O3S: C, 70.75; H, 5.92. Found: C, 70.65; H, 5.81.

6-Ethoxycarbonyl-3-(2-phenylethyl)tetrahydropyran-2-ones (37 and 38)

37

Colorless oil.

IR (neat): 2932, 1740 (C=O), 1377, 1203, 1108, 1030, 752 cm–1.

1H NMR: δ = 1.28 (t, J = 7.2 Hz, 3 H), 1.60–1.72 (m, 1 H), 1.75–1.87 (m, 1 H), 1.94–2.15 (m, 2 H), 2.21–2.34 (m, 2 H), 2.42–2.52 (m, 1 H), 2.65–2.82 (m, 2 H). 4.24 (q, J = 7.2 Hz, 2 H), 4.87 (dd, J = 7.4, 5.4 Hz, 1 H), 7.17–7.22 (m, 3 H).

MS: m/z (%) = 276 (M+, 2), 203 (20), 172 (69), 154 (30), 126 (40), 108 (54), 104 (21), 91 (100), 77 (8).

HRMS: m/z calcd for C16H15O3S (M+): 276.1360; found: 276.1366.

38

Colorless oil.

IR (neat): 2932, 1748 (C=O), 1379, 1196, 1114, 1029, 751 cm–1.

1H NMR: δ = 1.30 (t, J = 7.2 Hz, 3 H), 1.55–1.68 (m, 1 H), 1.84 (ddddd, J = 13.5, 9.1, 7.4, 5.8 Hz, 1 H), 1.98–2.09 (m, 1 H), 2.10–2.23 (m, 2 H), 2.25–2.37 (m, 1 H), 2.40–2.50 (m, 1 H), 4.19–4.35 (m, 2 H), 4.90 (t, J = 4.9 Hz, 1 H), 7.17–7.23 (m, 3 H), 7.26–7.31 (m, 2 H).

MS: m/z (%) = 276 (M+, 3), 203 (30), 172 (94), 154 (42), 126 (54), 108 (66), 104 (22), 91 (100), 77 (8), 65 (11).

HRMS: m/z calcd for C16H15O3S (M+): 276.1360; found: 276.1354.

4-Phenyl-5-(toluene-4-sulfanyl)dihydrofuran-2-one (39a)

Colorless crystals (ca. 9:1 mixture of two diastereomers); mp 94–108 °C (EtOAc–hexane).
IR (KBr): 2924, 1792 (C=O), 1494, 1146, 1039, 813 cm$^{-1}$.

1H NMR: $\delta = 1.40$–1.69 (m, 1.8 H), 1.78–1.96 (m, 0.2 H), 2.09, 2.13 (d, $J = 3.3$ Hz, 0.05 H each), 2.25, 2.29 (d, $J = 3.3$ Hz, 0.45 H each), 2.32–2.40 (m, 2 H), 2.42 (s, 2.7 H), 2.44 (s, 2.7 H), 2.86–2.99 (m, 2 H), 4.72 (d, $J = 2.5$ Hz, 0.9 H), 4.82 (d, $J = 2.3$ Hz, 0.1 H), 6.94–7.27 (m, 5 H), 7.33 (d, $J = 8.2$ Hz, 2 H), 7.47 (d, $J = 8.2$ Hz, 2 H).

MS: $m/z$ (%) = 329 ([M + H]$^+$), 21, 311 (39), 263 (20), 190 (10), 129 (100), 91 (25).

HRMS: $m/z$ calcd for C$_{15}$H$_{18}$O$_3$ (M$^+$): 288.1215; found: 288.1210.

5-Benzoyl-1-(2-phenylethyl)dihydrofuran-2-one (41c)

Colorless oil.

IR (neat): 2927, 1781 (C=O), 1693, 1452, 1170, 1022, 840 cm$^{-1}$.

1H NMR: $\delta = 1.79$–1.81 (m, 2 H), 2.00–2.02 (m, 1 H), 2.54–2.79 (m, 4 H), 5.43 (d, $J = 3.4$ Hz, 1 H), 7.14–7.32 (m, 5 H), 7.45–7.52 (m, 2 H), 7.59–7.66 (m, 1 H), 7.92–7.95 (m, 1 H), 8.09–8.12 (m, 1 H).

MS: $m/z$ (%) = 294 (M$^+$, 10), 276 (6), 266 (3), 190 (30), 189 (70), 125 (25), 144 (22), 105 (100), 91 (70), 77 (35).

HRMS: $m/z$ calcd for C$_{15}$H$_{18}$O$_3$ (M$^+$): 294.1256; found: 294.1261.

5-Ethoxycarbonyl-1-(4-phenyl)dihydrofuran-2-one (41d)

Colorless oil.

IR (neat): 2928, 1790 (C=O), 1747 (C=O), 1466, 1378, 1169, 1022, 839 cm$^{-1}$.

1H NMR: $\delta = 0.81$–0.96 (m, 6 H), 1.21–1.40 (m, 8 H), 1.64–1.76 (m, 2 H), 2.22–2.36 (m, 1 H), 4.26 (q, $J = 6.9$ Hz, 2 H), 4.56 (d, $J = 4.3$ Hz, 1 H).

MS: $m/z$ (%) = 242 (M$^+$, 2), 169 (51), 151 (10), 139 (6), 123 (10), 109 (100), 92 (17), 85 (26), 69 (35).

HRMS: $m/z$ calcd for C$_{15}$H$_{18}$O$_3$ (M$^+$): 242.1518; found: 242.1520.

2-Oxaspiro[4.4]nonadecan-3-one (41f, E = H)

Colorless crystals; mp 160–161 °C (EtOH–H$_2$O).

IR (neat): 2932, 1785 (C=O), 1459, 1380, 1144, 1089, 1021 cm$^{-1}$.

1H NMR: $\delta = 0.86$–0.89 (m, 6 H), 1.26–1.70 (m, 10 H), 1.84–1.90 (m, 1 H), 2.17–2.30 (m, 2 H), 5.44 (d, $J = 3.2$ Hz, 1 H), 7.50–7.54 (m, 2 H), 7.60–7.68 (m, 1 H), 7.96–7.98 (m, 2 H).

MS: $m/z$ (%) = 274 (M$^+$, 2), 170 (2), 154 (4), 139 (9), 114 (32), 105 (61), 83 (47), 69 (54), 56 (100).

HRMS: $m/z$ calcd for C$_{15}$H$_{18}$O$_3$ (M$^+$): 274.1569; found: 274.1573.

8-Oxaspiro[4.4]nonadecan-3-one (41f, E = H)

Colorless crystals; mp 53–54 °C (EtOH–H$_2$O).

IR (KBr): 2929, 1787 (C=O), 1459, 1170, 1025 cm$^{-1}$.

1H NMR: $\delta = 1.31$–1.52 (m, 28 H), 2.32 (s, 2 H), 4.01 (s, 2 H).

MS: $m/z$ (%) = 280 (M$^+$, 22), 249 (100), 222 (29), 55 (47), 41 (45).

HRMS: $m/z$ calcd for C$_{15}$H$_{18}$O$_3$ (M$^+$): 280.2401; found: 280.2412.


8-[4-(4-Methoxyphenyl)ethyl]-4-methyl-5-(2-tolylsulfinyl)dihydrofuran-2-one (39d)

Colorless crystals; mp 76–78 °C.

IR (neat): 2924, 1792 (C=O), 1588, 1155, 1048 (S=O), 1022, 843, 812 cm$^{-1}$.

1H NMR: $\delta = 1.23$–1.54 (m, 28 H), 2.26, 2.89 (d, $J = 17.4$ Hz, 0.8 H each), 2.40, 2.64 (d, $J = 17.7$ Hz, 0.2 H each), 2.42 (s, 2.4 H), 2.43 (s, 0.6 H), 4.49 (s, 1 H), 7.34, 7.52 (d, $J = 8.0$ Hz, 1.6 H each), 7.35, 7.58 (d, $J = 8.0$ Hz, 0.4 H).

MS: $m/z$ (%) = 418 (M$^+$, trace), 276 (100), 249 (12), 219 (8), 124 (25), 93 (31), 55 (27).

HRMS: $m/z$ calcd for C$_{25}$H$_{38}$O$_3$S (M$^+$): 418.2542; found: 418.2540.
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References


