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A six-step total synthesis of α-thujone and d_6-α-thujone, enabling facile access to isotopically labelled metabolites†

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The short synthesis of α-thujone relies on the functionalization of the readily available dimethylfulvene. Furthermore, the three main metabolites of the natural product were also synthesized. Since d_6-acetone can be used as a starting material, the route developed allows for the facile incorporation of isotopic labels which are required for detecting and quantifying trace amounts *via* GC/MS analysis.

A great variety of plants produce the monoterpenes α-thujone (**1a**) and β-thujone (**2**, Fig. 1), which therefore are present in diverse herbal products.[1] The most famous product containing thujone is certainly absinth, produced from wormwood. It had been a popular spirit drink in the 19th century but later was prohibited due to concerns about its toxicity.[2] It was connected to severe health problems, including hallucinations, depressions, convulsions, blindness and mental deterioration. More recent studies propose that most of these effects were caused by alcohol intoxication.[2] Nevertheless, thujone is neurotoxic and was shown to inhibit the gamma-aminobutyric acid A (GABAA) receptor, which leads to excitations and convulsions at higher concentrations in animal studies.[3] α-Thujone (**1a**) was shown to be more active than its β-isomer **2**. The metabolism of thujone was investigated both *in vitro* and *in vivo*. 7-OH-α-thujone (**3a**) is clearly the major metabolite in *in vitro* studies.[3] *In vivo* studies, however, point to 2-OH-α-thujone (**4a**) and 4-OH-α-thujone (**5a**) as the main metabolites.[4]

The manufacture of thujone containing products is permitted again in the European Union but maximum limits have been imposed.[5] To ensure accurate quantitation, to assess whether these products meet the requirements and additionally to better detect trace amounts of α-thujone and its major metabolites, access to isotopically labelled derivatives is required. Although the structure of the bicyclic monoterpene was elucidated in 1900 by Semmler,[6] only one total synthesis has been reported so far.[7] Oppolzer *et al.* prepared enantioenriched α-thujone over twelve steps from commercially available materials, utilizing an elegant palladium-catalyzed cyclization strategy. The route, however, does not allow for a facile introduction of inexpensive isotopic labels. Therefore, we developed and herein describe a novel six-step access to α-thujone, which enables the introduction of isotopic labels from inexpensive d_6-acetone. The synthesized d_6-thujone **1b** thereafter is also functionalized to the most important metabolites **3b**, **4b** and **5b**.

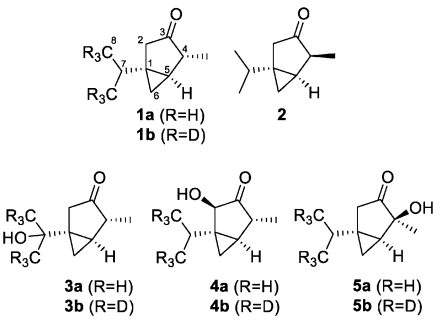

Fig. 1 Structures of α-thujone (**1a**), β-thujone (**2**) and the major metabolites of α-thujone: 7-OH-α-thujone (**3a**), 2-OH-α-thujone (**4a**), and 4-OH-α-thujone (**5a**).

Our synthetic strategy is based on a late-stage oxidation of alcohol **6a**/**6b** (Scheme 1), followed by a regio- and diastereoselective methylation at position C4. Such an approach seemed attractive since alcohol **6a**/**6b** should be directly accessible from cyclopentenol **7a**/**7b** *via* Simmons–Smith cyclopropanation.[8] Cyclopentenol **7a**/**7b** can be traced back to the known dimethylfulvenes **8a** and **8b**, which are synthesized from cyclopentadiene and acetone.[9] Therefore, the inexpensive d_6-acetone can function as the source of the isotopic labels.

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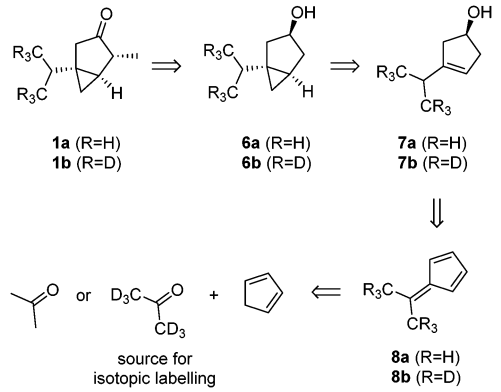
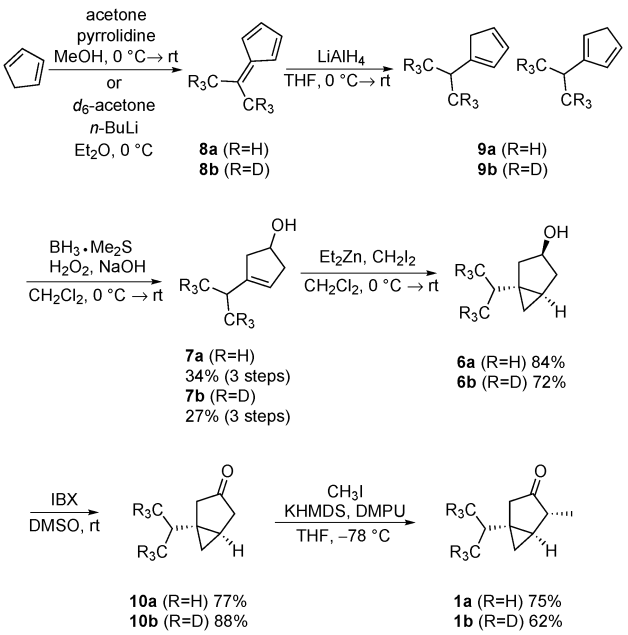


Scheme 1 Retrosynthetic analysis of α-thujone (**1a**) and its deuterated derivative **1b**.

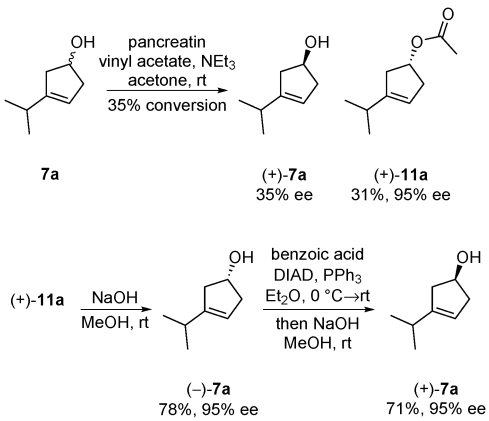
Our synthesis commenced with the formation of dimethylfulvene (Scheme 2). The preparation of **8a** followed a procedure described by Little *et al.*, utilizing pyrrolidine as a base.[9a] This procedure was not suitable for the preparation of the d_6-dimethylfulvene **8b**, since the deuterium label was partially removed, presumably *via* enamine formation. Therefore, the procedure introduced by the group of Gajewski was utilized to prepare d_6-dimethylfulvene **8b**.[9b] Using *n*-butyllithium as a base, a deuteration degree of 95.5% was achieved. The dimethylfulvenes formed were reduced with lithium aluminium hydride to yield a mixture of cyclopentadienes. It is known that related mixtures can be converted convergently to a single alcohol product *via* the hydroboration/oxidation sequence.[10] Indeed, such a procedure yielded, after purification by chromatography, alcohols **7a** and **7b** in 34% and 27% yield over three steps, respectively. Cyclopropanation was performed utilizing the Furukawa modification of the Simmons–Smith reaction.[11] After oxidation utilizing 2-iodoxybenzoic acid (IBX) as an oxidant,[12] ketones **10a**/**10b** were obtained in 77% and 88% yield, respectively. The final alkylation step required careful optimization of the reaction conditions. It was found that multi-alkylated products could not be separated by flash chromatography. Therefore, the reaction conditions were optimized to produce **1a**/**1b** selectively. The use of 1.0 eq. of potassium bis(trimethylsilyl)amide and methyl iodide, as well as the addition of *N*,*N*′-dimethylpropyleneurea, facilitated this task. Thujones **1a** and **1b** were obtained in 75% and 62% yield, respectively.

Although an optically active material is not required for use as an internal standard in GC/MS or LC/MS analysis, it may be helpful for other applications. Therefore, we investigated the possibility of performing the hydroboration of the cyclopentadienes **9a** in an enantioselective fashion. Attempts with diisopinocampheylborane[13] only lead to very low levels of enantiomeric enrichment (11% ee). It was therefore decided to turn to kinetic resolution. Pancreatin was utilized for the kinetic resolution of a structurally related cyclopentenol,[14] and also proved to be effective in this case. Kinetic resolution provided acetate (+)-**11a** in high optical purity (95% ee) and acceptable conversion (35%) (Scheme 3). Alcohol (+)-**7a**, the enantiomer required, was not accessible efficiently *via* kinetic resolution. Time-consuming repetitions of kinetic resolutions were required to increase the conversions and enantiomeric excess. It turned out to be advantageous to work with acetate (+)-**11** and invert its stereocenter *via* the Mitsunobu reaction. This three-step procedure delivered (+)-**7a** in high optical purity (95% ee). This material was converted to optically active thujone (−)-**1a** (95% ee) as described in Scheme 2 (see the ESI†).

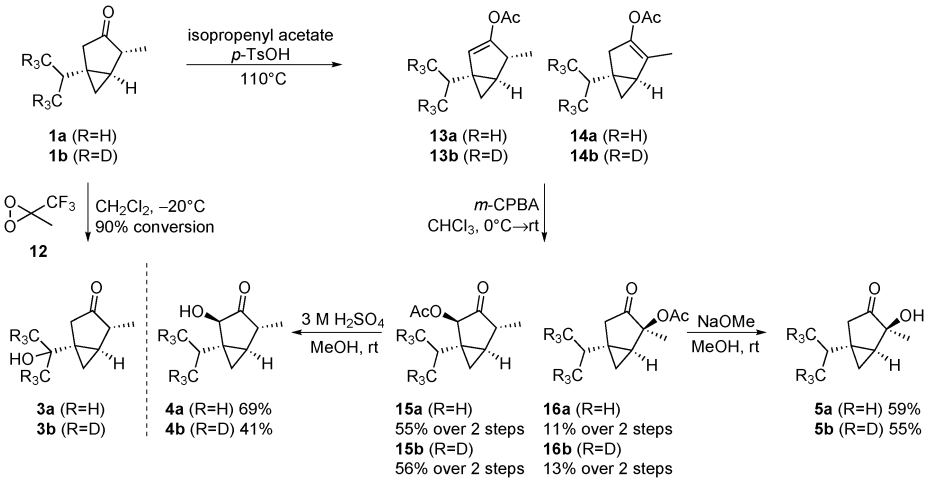
After having developed a concise route to thujone (**1a**) and its isotopically labelled derivative **1b**, we turned to the preparation of the most important metabolites. The oxidation of **1a** to 7-OH-α-thujone (**3a**) was described in the literature utilizing ozone as the oxidant.[15] However, these conditions lead to considerable overoxidation and a reduced yield of **3a** (47%). After screening several oxidants, we found that methyl(trifluoromethyl)dioxirane[16] (TFDO, **12**) led to a clean conversion to **3a** (Scheme 4). For the synthesis of the 4-hydroxy derivative **5a**, we followed the procedure of the group of Casida.[17] First, the



Scheme 2 Synthesis of thujone **1a**/**1b**.



Scheme 3 Kinetic resolution of (±)-3-isopropylcyclopent-3-en-1-ol and inversion of the chiral center *via* Mitsunobu reaction.



Scheme 4 Synthesis of the hydroxylated main metabolites.

enolacetate is formed by refluxing thujone in isopropenyl acetate under acidic conditions. In contrast to the literature, we observed the 2,3-enol acetate **13a** as the main product (**13a**:**14a** = 8:2). Therefore, we decided to utilize this mixture to obtain both the 2-hydroxy and the 4-hydroxy derivative at once. The inseparable mixture was oxidized with 3-chloroperoxybenzoic acid. In both cases epoxidation was preferred from the convex bottom face, delivering after migration of the acetate group the desired diastereoisomers **15** and **16**. The isomers were separated by chromatography, and subsequently deprotected to yield the metabolites **4** and **5**, respectively. Deprotection of **15** was successful only under acidic conditions, as regular basic hydrolysis led to decomposition of the material.

In summary, we have developed a concise route to α-thujone, which relies on the functionalization of dimethylfulvene. The synthesis allows for the facile incorporation of inexpensive isotopic labels by utilizing d_6-acetone as a starting material. Furthermore, the three main metabolites of α-thujone were prepared.

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