The Synthesis of Novel Fluorine-Containing Natural and Unnatural Compounds

Thesis

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The Synthesis of Novel Fluorine-Containing Natural and Unnatural Compounds

Submitted by

Levan Pivnevi

to The Open University as a thesis for the degree of Doctor of Philosophy in Chemistry.

September 2004
The project was divided into three parts:

1. Synthesis of perfluoro (highly fluorinated chain) compounds

The aim was to prepare modified phosphorous and nitrogen containing organic molecules by attaching to them highly fluorinated tags. A review of the current literature in the area is given. The fluorous compounds at room temperature are typically immiscible with organic solvents and water. The method gives an advantage of simple liquid-liquid separation and in some cases an opportunity to recover partially the starting materials.

2. Synthesis of fluorine containing heterocyclic compounds

The incorporation of fluorine in heterocyclic compounds may have only a small effect on their conformation, but may have a large electronic effect. This may give rise to novel biological activity. A review of the current literature in the area is given. Using simple aldehydes as starting materials, in the presence of Lewis acids, a straightforward procedure has been developed to prepare fluorinated heterocycles.

3. Synthesis of heterocyclic natural products

Using a related method to the one previously developed in part 2, the same Lewis acid promoted reaction has been applied to the total synthesis of two physiologically active natural products.

Finally, the experimental details for each of the above three sections will be given.

The work described in this thesis is the author's own work, accept where appropriate reference is made. Work previously published by a colleague (*Tetrahedron Lett.*, 2002, 43, 2807-2810) has been repeated herein and the results optimised.
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Ac</td>
<td>Acetyl</td>
</tr>
<tr>
<td>acac</td>
<td>acetylacetone</td>
</tr>
<tr>
<td>Ar</td>
<td>Aryl</td>
</tr>
<tr>
<td>ATPH</td>
<td>Aluminium tris(2,6-diphenylphenoxide)</td>
</tr>
<tr>
<td>Bn</td>
<td>Benzyl</td>
</tr>
<tr>
<td>Bu</td>
<td>Butyl</td>
</tr>
<tr>
<td>BTF</td>
<td>Benzotrifluoride, C₈H₇CF₃</td>
</tr>
<tr>
<td>Bz</td>
<td>Benzoyl</td>
</tr>
<tr>
<td>C</td>
<td>Concentration</td>
</tr>
<tr>
<td>CI</td>
<td>Chemical ionisation</td>
</tr>
<tr>
<td>Cp</td>
<td>Cyclopentadienyl</td>
</tr>
<tr>
<td>DAST</td>
<td>Diethylaminosulfurtrifluoride</td>
</tr>
<tr>
<td>DCM</td>
<td>Dichloromethane</td>
</tr>
<tr>
<td>DEAD</td>
<td>Diethyl azodicarboxylate</td>
</tr>
<tr>
<td>DIBAL-H</td>
<td>Diisobutylaluminium hydride</td>
</tr>
<tr>
<td>DMSO</td>
<td>Dimethyl sulfoxide</td>
</tr>
<tr>
<td>EI</td>
<td>Electron impact</td>
</tr>
<tr>
<td>eq.</td>
<td>Equivalent</td>
</tr>
<tr>
<td>FBC</td>
<td>Fluorous Biphasic Catalysis</td>
</tr>
<tr>
<td>FBS</td>
<td>Fluorous Biphasic System</td>
</tr>
<tr>
<td>FC-72</td>
<td>Perfluorohexane</td>
</tr>
<tr>
<td>FDEAD</td>
<td>Fluorous Diethylidiazocarboxilate</td>
</tr>
<tr>
<td>fod</td>
<td>tris-(6,6,7,8,8,8)Heptafluoro-2,2-dimethyl-3,5-octanedionate</td>
</tr>
<tr>
<td>FRPS</td>
<td>Fluorous Reverse Phase Silica</td>
</tr>
<tr>
<td>GC</td>
<td>Gas chromatography</td>
</tr>
<tr>
<td>h</td>
<td>Hours</td>
</tr>
<tr>
<td>Hal</td>
<td>Halogen</td>
</tr>
<tr>
<td>HLE</td>
<td>Horse liver esterase</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>IR</td>
<td>Infra red</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
</tr>
<tr>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>ISMS</td>
<td>Intramolecular silyl modified Sakurai</td>
</tr>
<tr>
<td>kJ</td>
<td>Kilojoule</td>
</tr>
<tr>
<td>LDA</td>
<td>Lithium diisopropylamide</td>
</tr>
<tr>
<td>M</td>
<td>Molarity</td>
</tr>
<tr>
<td>MABR</td>
<td>methylaluminium bis(4-bromo-2,6-di-tert-butylphenoxide)</td>
</tr>
<tr>
<td>m-CPBA</td>
<td>meta-chloroperoxybenzoic acid</td>
</tr>
<tr>
<td>MAD</td>
<td>methylaluminium bis(2,6-di-tert-butyl-4-methylphenoxide)</td>
</tr>
<tr>
<td>MAPH</td>
<td>methylaluminium bis(2,6-diphenylphenoxide)</td>
</tr>
<tr>
<td>Ms</td>
<td>Mesyl (methanesulfonyl)</td>
</tr>
<tr>
<td>MHz</td>
<td>megahertz</td>
</tr>
<tr>
<td>MOM</td>
<td>Methoxymethyl</td>
</tr>
<tr>
<td>Mp</td>
<td>Melting point</td>
</tr>
<tr>
<td>MS</td>
<td>Mass spectrometry</td>
</tr>
<tr>
<td>m/z</td>
<td>mass to charge ratio</td>
</tr>
<tr>
<td>NBS</td>
<td>N-Bromosuccinimide</td>
</tr>
<tr>
<td>nm</td>
<td>Nanometer</td>
</tr>
<tr>
<td>NMO</td>
<td>4-Methylmorpholine N-oxide</td>
</tr>
<tr>
<td>NOE</td>
<td>Nuclear Overhauser enhancement</td>
</tr>
<tr>
<td>NMR</td>
<td>Nuclear magnetic resonance</td>
</tr>
<tr>
<td>Nu</td>
<td>Nucleophile</td>
</tr>
<tr>
<td>P</td>
<td>Protecting group</td>
</tr>
<tr>
<td>Ph</td>
<td>Phenyl</td>
</tr>
<tr>
<td>Petrol</td>
<td>Petroleum ether (40-60 °C)</td>
</tr>
<tr>
<td>Piv</td>
<td>Pivaloyl</td>
</tr>
<tr>
<td>PFMC</td>
<td>Perfluoromethylcyclohexane</td>
</tr>
<tr>
<td>PMHS</td>
<td>Polymethylhydrosiloxane</td>
</tr>
<tr>
<td>PPL</td>
<td>Porcine pancreatic lipase</td>
</tr>
<tr>
<td>ppm</td>
<td>parts per million</td>
</tr>
<tr>
<td>PPTS</td>
<td>Pyridinium p-toluenesulfonate</td>
</tr>
<tr>
<td>Pr</td>
<td>Propyl</td>
</tr>
<tr>
<td>Py</td>
<td>Pyridine</td>
</tr>
<tr>
<td>RCM</td>
<td>Ring closing metathesis</td>
</tr>
<tr>
<td>Abbreviations</td>
<td>Description</td>
</tr>
<tr>
<td>---------------</td>
<td>-------------</td>
</tr>
<tr>
<td>rt</td>
<td>room temperature</td>
</tr>
<tr>
<td>TBC</td>
<td>Twist-boat-chair</td>
</tr>
<tr>
<td>TDP</td>
<td>4,4'-Thiodiphenol</td>
</tr>
<tr>
<td>TEMPO</td>
<td>Tetramethylpiperidine-1-oxyl</td>
</tr>
<tr>
<td>THF</td>
<td>Tetrahydrofuran</td>
</tr>
<tr>
<td>TLC</td>
<td>Thin layer chromatography</td>
</tr>
<tr>
<td>tol</td>
<td>Toluene</td>
</tr>
<tr>
<td>TBDMS</td>
<td>tert-Butyldimethylsilyl</td>
</tr>
<tr>
<td>TBDPS</td>
<td>tert-Butyldiphenylsilyl</td>
</tr>
<tr>
<td>Tf</td>
<td>Trifluoromethanesulfonyl</td>
</tr>
<tr>
<td>TIPS</td>
<td>Triisopropylsilyl</td>
</tr>
<tr>
<td>TMS</td>
<td>Trimethylsilyl</td>
</tr>
<tr>
<td>Ts</td>
<td>p-Toluenesulfonyl</td>
</tr>
<tr>
<td>WSPA</td>
<td>World Society for the Protection of Animals</td>
</tr>
</tbody>
</table>
Acknowledgements

I would like to thank my supervisors Dr. Adrian Dobbs and Dr. Jim Iley for selecting me and giving me the opportunity of obtaining a PhD degree and for all their help, enthusiasm and encouragement during the last three and a half years. I would like to thank all the members of staff at the Department of Chemistry of the Open University and the School of Chemistry, University of Exeter for their help and advice throughout my work.

The work described in this thesis was funded by the Open University. Its financial support is gratefully acknowledged. I am most grateful to Ms. Alison Robinson and Ms. Paula Cole and the Open University Research School for their massive support. They were always happy to help me at any time.

I would like to thank the whole technical staff of both universities, particularly Dr. Ivan Prokes for his timely NMR spectroscopy service and Mr Eric Underwood for his great help as much with MS spectroscopy analysis as on a rugby pitch.

I would like to thank everybody who worked with me in the labs during all these years. I appreciate their patience and support and their ability to create a nice working environment. Many thanks to Zhaohui, Sasa, Georgia, Sharon, Jayne, Antonio, Sebastian, Nikky, David and all others from whom I gained all the necessary knowledge for lab works. My special thanks to all my friends in Georgia, UK, USA, Germany, China, Ukraine, Russia, Dominican Republic, Spain, Switzerland and Venezuela, without their great support I would not have been able to finish.

My very special thanks to my family: to my mum, my dad and indeed to my precious daughter Ana, who has been growing up without my attention for all this period. I would like to show my gratitude to them, my biggest supporters in this world.

Thanks to everybody for making my life more colourful; thanks to the British people for “adopting” me for all these years and giving me the chance to taste distinctive real cask ale!
Chapter 1

INTRODUCTION
1.1 Introduction to Organofluorine Chemistry

Fluorine is the ninth element in the Periodic Table with an exact atomic mass of 18.998. It is a member of group VII, the halogens. Fluorine constitutes 0.078% of the earth’s crust and on limited occasions free fluorine has been encountered in minerals. The most important fluorine-containing mineral is fluorospar – calcium difluoride CaF₂. Fluoride ion is found in natural water as well as seawater (0.3 mg per litre).

Fluorine is a pale yellow colour halogen gas, reacting easily at room temperature with all metals. The metals, which do not burn, obtain a protective covering of the corresponding metal fluoride. Nickel and some middle weight metal alloys are used to handle fluorine on a large scale.¹

Emeleus defined three main factors to explain why the chemistry of fluorine is different from the other halogens:

1. *The low bond dissociation energy of the fluorine molecule*

Table 1: The bond dissociation energies of the halogen-halogen bond: ¹

<table>
<thead>
<tr>
<th>Bond</th>
<th>Energy (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F₂</td>
<td>158</td>
</tr>
<tr>
<td>Cl₂</td>
<td>242</td>
</tr>
<tr>
<td>Br₂</td>
<td>193</td>
</tr>
<tr>
<td>I₂</td>
<td>151</td>
</tr>
</tbody>
</table>

It is interesting to note that although iodine has nearly the same bond dissociation value as fluorine, it creates much weaker bonds. Thus, the formation of fluorides releases more energy.

2. *The relatively high strength of bonds formed between fluorine and non-metallic elements*

Table 2: Assorted bond strengths¹

<table>
<thead>
<tr>
<th>Bond</th>
<th>Energy (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-F (HF)</td>
<td>565</td>
</tr>
<tr>
<td>H-Cl (HCl)</td>
<td>431</td>
</tr>
<tr>
<td>H-Br (HBr)</td>
<td>364</td>
</tr>
<tr>
<td>H-I (HI)</td>
<td>297</td>
</tr>
<tr>
<td>C-F (CF₄)</td>
<td>485</td>
</tr>
<tr>
<td>C-Cl (CCl₄)</td>
<td>326</td>
</tr>
<tr>
<td>C-Br (CBr₄)</td>
<td>242</td>
</tr>
<tr>
<td>C-I (CI₄)</td>
<td>238</td>
</tr>
</tbody>
</table>
3. The relatively small size of the fluorine atom and the fluoride ion

Table 3: Comparative radii of various elements

<table>
<thead>
<tr>
<th>Element</th>
<th>Covalent radius, nm:</th>
<th>Ionic radius, nm:</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>0.064</td>
<td>0.136</td>
</tr>
<tr>
<td>Cl</td>
<td>0.099</td>
<td>0.181</td>
</tr>
<tr>
<td>Br</td>
<td>0.114</td>
<td>0.195</td>
</tr>
<tr>
<td>I</td>
<td>0.133</td>
<td>0.216</td>
</tr>
<tr>
<td>O</td>
<td>0.066</td>
<td>0.140</td>
</tr>
</tbody>
</table>

As shown in Table 3, the radii of F⁻ and O²⁻ are nearly the same. This factor leads to a close similarity in the structures of many ionic fluorides and oxides of the same type.²

For many years, the fluorine containing mineral fluorospar has been used as a metallurgical flux. The first studies were done by Marggraf in 1768 by distillation of fluorospar with sulfuric acid.¹ However, elemental fluorine was first isolated in 1886 by Moissan³, and a decade later the Belgian chemist Swarts described the synthesis of methyl fluoroacetate by heating methyl iodoacetate with silver fluoride.⁴ This synthesis heralded the beginnings of modern fluoro-organic chemistry and later, in 1922, Swarts prepared trifluoroacetic acid⁵ and by doing so, laid the foundations for all subsequent organofluorine chemistry. Numerous fluorocarbons were prepared in the years following, for example fluorocarbon polymers (thermally and chemically stable refrigerants and lubricants) and, more recently, aerosol propellants, fire extinguishing agents, anesthetics and blood substitutes.

The biological effects of introducing fluorine into organic molecules were first studied during World War II by both British and German scientists, but it was the demonstration by Marais, in 1943,⁵ that the toxicity of the South African plant Dichapetalum cymosum was due to monofluoroacetate that provided the impetus for studies on the toxicology and pharmacology of organofluorine compounds. Later studies⁶,⁷ revealed that monofluoroacetate is incorporated into the citric acid cycle, and the enzyme aconitase becomes completely and irreversibly inhibited. This had significant implications for the rational design of enzyme inhibitors, which can be used to great effect in the pharmaceutical industry.
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Research in the early 1950s led to the discovery that certain fluorosteroids can actually surpass naturally occurring hormones in their biological activity. The discovery boosted enormously the research in dealing with the introduction of fluorine at specific sites in biologically active molecules. Nowadays such fluorinated analogues are highly desirable targets and research into new synthetic routes to organofluorine compounds continues.

1.2 The Effects of Introducing Fluorine Into Organic Molecules

There are three main explanations as to why the introduction of fluorine can lead to desirable changes in the properties and biological activity of organic compounds:

(i) Steric Effects

Fluorine has a van der Waals radius of 0.155 nm making it the smallest substituent after hydrogen (van der Waals radius 0.12 nm). Also, the average C-F bond length (0.138 nm) is only marginally greater than the average C-H bond length (0.108 nm).

The size of fluorine is also comparable to that of the hydroxyl group, with the van der Waal radius of oxygen being 0.150 nm. The average C-O bond length is 0.143 nm which, again, is very similar to the average C-F bond length.

(ii) Electronic Effects

Fluorine has an electronegativity value of 4.0 on the Pauling electronegativity index and is the most electronegative of all the elements. This is very much greater than hydrogen, which has a value of just 2.1. Oxygen however, with a value of 3.5, is also highly electronegative and thus fluorine may be able to mimic oxygen and function as a hydrogen bond acceptor.

The high electronegativity of fluorine creates a large $\delta^+$ on adjacent carbon centres and since fluoride is a relatively good leaving group, nucleophilic attack may occur on the adjacent carbon, displacing the fluoride and leaving the possibility of the remaining organic moiety covalently bonded to another organic compound, for example an enzyme. Having said this, the C-F bond is strong, 485 kJ mol$^{-1}$, thus protecting it from unwanted metabolic transformations. Substitution of a hydrogen atom or hydroxyl group by fluorine in
enzyme substrate analogues is widely used in various fields of bioorganic and medicinal chemistry.\textsuperscript{11}

The presence of fluorine has a marked effect on the $pK_a$ value of the most acidic hydrogen/hydrogens in a molecule. For example, the $pK_a$ of acetic acid, $\text{CH}_3\text{COOH}$, is 4.76, and the substitution of a single hydrogen on the methyl group for a single fluorine to give fluoroacetic acid, $\text{CH}_2\text{FCOOH}$, increases the acidity to give a $pK_a$ value of 2.66.\textsuperscript{10}

(iii) Lipophilicity

Any C-F bonds in a molecule will substantially increase its lipophilicity. This is of considerable importance in drug design since crossing the phospholipid bilayer of cell membranes is essential if the drug is designed to act within the cell.

1.3 Specific Replacements

The prospects discussed in section 1.2, either individually or in combination, may lead to specific effects when certain atoms or functional groups are replaced by the corresponding number of fluorine atoms.

(i) Replacement for Hydrogen

Replacement of a single hydrogen atom with fluorine introduces only a small steric and geometric perturbation relative to the hydrocarbon counterpart,\textsuperscript{12} and if the replacement is within an analogue of an enzyme substrate, the affinity for the target enzyme is usually high.\textsuperscript{11} The close isosteric relationship between fluorine and hydrogen, due to the van der Waals radii and bond lengths mentioned in 1.2, makes the introduction of a single fluorine into a biologically active molecule a very useful step since the compound can benefit enormously from the increased lipophilicity and the other unique properties fluorine creates without compromising compatibility for the target.

(ii) Replacement for the Hydroxyl Group

The capacity for organofluorine compounds to act as a hydroxyl mimic has been widely discussed,\textsuperscript{13,14} but recent theoretical and crystallographic evidence force the conclusion that fluorine is a poor hydrogen bond acceptor with only a moderate capacity to replace oxygen, or indeed nitrogen, in this role.\textsuperscript{11} Although there are examples in the literature which
clearly suggest that fluorine can replace OH as a hydrogen bond acceptor, more often than not the substitution proves detrimental since hydrogen bonding is probably the most significant interaction when considering enzyme substrate binding.

(iii) Replacement for the Ethylene Group

The most significant effect of introducing the CF$_2$ group into an organic molecule is the difference in bond angle between C-CH$_2$-C and C-CF$_2$-C. The C-CH$_2$-C bond angle is typically 109° whereas the C-CF$_2$-C angle ranges from 111°C to 119.9°. The introduction of the difluoromethyl group can, therefore, lead to conformational changes in the rest of the molecule, which can alter the physical properties in relation to its hydrocarbon counterpart. In this respect CF$_2$ is a less than ideal CH$_2$ mimic for biochemical applications.

1.4 Introduction to Fluorous Chemistry

The yield of all chemical reactions are limited both by the efficiency of the reaction and also by the ability to obtain pure product. The transformation of a starting material into a new, desired product is a process that can be divided into three stages: (Scheme 1)

1) Reaction

\[ \text{Substrate} \rightarrow \text{reactant(s)} \rightarrow \text{reagent(s)} \rightarrow \text{product + byproducts + recovered reaction components} \]

2) Purification

\[ \text{Product is characterised by NMR, IR, MS, X-ray, HPLC etc.} \]

3) Identification/Analysis

The primary purification of an organic mixture by "workup" has changed little over the last few decades. Further, the methods of crystallisation, distillation, chromatography are basically similar to those 20 years ago. The development of combinatorial chemistry and automated parallel synthesis has begun a revolution in the way synthesis is carried out, since these methods require simple purification techniques.
In recent years, several new techniques have developed for the purification of reactions and one of them is fluorous phase chemistry. The initial works were published in the early 1990’s, with the most influential by Horváth and Rábai in 1994. Horváth and others have since developed, in more detail, the concept of fluorous chemistry.

The term ‘fluorous’ is spreading widely across the chemical community. It is well known as a similar name to ‘aqueous’ for water-based systems. Thus, it means highly fluorinated. The term perfluorinated is also widely used and is almost synonymous.

1.5 Fluorous Molecules

Fluorous molecules are designed to react and behave as organic analogues in terms of their reactivity, but also be easily separable from other organic molecules by value of their high fluorine content. A typical fluorous molecule includes two domains, a highly fluorinated group, which controls the fluorous solubility of the molecule and an organic domain, which directs the reactivity of the compound and resembles a standard organic molecule. Molecules 2, 4 are two simple examples of fluorous molecules to illustrate this concept. Their design is based on the parent organic molecules 1 and 3.

\[
\begin{align*}
\text{Organic Compound} & \quad \text{Fluorous Compound} \\
(C_4H_9)_3SnH & \quad (C_8F_{13}CH_2CH_2)_3SnH \\
\text{a typical organic tin hydride} & \quad \text{a typical fluorous tin hydride} \\
\text{mediates diverse radical reactions,} & \quad \text{mimics the reactivity of its organic parent, is easy} \\
\text{but it is difficult to separate from organic} & \quad \text{to separate from organic products by liquid-liquid} \\
\text{products} & \quad \text{extraction; recovery and reuse are routine} \\
\text{triphenylphosphine} & \quad \text{fluorous-triphenylphosphine} \\
\text{common reagent in many organic reactions} & \quad \text{phosphorus centre reacts as in triphenylphosphine;} \\
\text{aromatic ring protects P from effects of fluorous chains} & \\
\end{align*}
\]

Fig. 1

Phosphine oxides 5 and phosphorus-metal complexes normally are difficult to remove from a reaction mixture, but in the case of having fluorous tags 6 the phosphine oxides can be removed easily by simple liquid-liquid extraction by using a solution of organic and perfluoro solvents to leave the mixture without any phosphine residue.
Fluorous tin compounds are also readily separable from organic compounds using simple fluorous liquid-liquid or solid-liquid extractions. The fluorous tag is always attached to the tin atom, incorporating a short spacer group between the tin and fluorous chain. Tin compounds are recovered at the end of the process and recycled.

1.6 Fluorous Solvents

"Fluorous solvent" is a term similar to "fluorous molecule" and means a highly fluorinated solvent. Many are now commercially available from different suppliers (3M, Fluorochem, Lancaster, Aldrich, Oxychem, PCR and Oakwood Products), sold in 80-90% purity. Currently a wide range of fluorous ethers and amines are available and a few of the most commonly used solvents are shown.
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The frequently used solvent perfluorohexane, FC-72 is an analogue of the organic solvent hexane. Fluorous solvents are immiscible with organic or water phases, but this is temperature dependant. At room temperature FC-72 (20 °C) does not mix with most organic solvents and forms a bilayer system. Even a slight rise in temperature can resolve this status quo, the two layers can become miscible at 24 °C depending on the organic solvent. Immiscibility was the paramount factor in early success of fluorous chemistry. Many fluorous chemists still rely on the liquid-liquid extraction technique as the primary technique for the separation.

Chemists are familiar with standard, four phase simple workup-level purification methods: the gas phase, the organic liquid phase, the aqueous liquid phase and the solid phase. Since fluorous chemistry has been adopted by the organic community, it has sometimes been defined as the fifth phase.

![Picture showing three immiscible phases](Picture is taken from www.fluorous.com)

Liquid-liquid extractions work better when fluorous domains are relatively large. For some cases only a single separation is needed. This method is used when the desired product is organic and other reaction component is fluorous.

However, the costs of perfluoro solvents forced chemists to find alternative solvents for fluorous chemistry. Benzotrichloride (BTF, C₆H₅CF₃) was introduced as a ‘light fluorous’ solvent for use as a reaction medium in place of the traditional organic/fluorous biphas. This solvent gives an advantage of dissolving both organic and fluorous molecules. Also, its price is reasonably low compared to perfluoro solvents. After completing the reaction, BTF can be removed by evaporation and the remaining crude mass extracted by liquid-liquid extraction with organic and fluorous solvents; the desired compound(s) can be
obtained by evaporation from the opposite phase. Thus, no perfluoro solvent is needed during the actual reaction. Flurous solvents can be stored and re-used many times.

Flurous molecules, like the solvents, are also expensive compared to their organic analogues. Decreasing the number of fluorine atoms in the molecule lowers the price, but raises the organic solubility of the compound and decreases the flurous solubility. This effect creates a problem when using liquid-liquid extractions, so ‘light flurous’ synthesis uses solid-liquid extractions where possible.

Fluorocarbon-bonded phase silica gel (technically called flurous reverse-phase silica, FRPS) may be used to adsorb flurous molecules and separate them from non-adsorbed organic ones. The first case of a silica gel with a fluorocarbon phase was reported in 1978, the silica being silylated with (heptadecafluorodecyl)dimethylsilyl chloride, ClSi(Me)$_2$CH$_2$CH$_2$C$_8$F$_{17}$. Currently, flurous silica with fluorocarbon phases has been developed and widely used by Fluorous Technologies Inc. including: -Si(Me)$_2$CH$_2$CH$_2$C$_6$F$_{13}$ and -Si(Me)$_2$(CH$_2$)$_3$C(CF$_3$)$_2$C$_3$F$_7$. Research has shown advantages of flurous silica over ordinary reverse phase silica gel for analytical and HPLC applications. Flurous silica also gives an opportunity to separate fluorinated and organic molecules from each other. Organic molecules pass easily through these fluorinated columns while flurous ones are retained to a high degree. In the separation process, a crude mixture is mixed with appropriate amount of silica gel and the silica is eluted first with a ‘fluorphobic’ solvent to remove the organic compound while leaving the flurous compound adsorbed. In situations where the flurous molecule is desired, a second elution with a ‘fluorophilic’ solvent gives this material.

In addition, flurous silica can be used to separate perfluoro compounds on the basis of fluorine content. Curran has employed this technique of flurous chromatography to separate a number of flurous compounds based on their fluorine content, from C$_3$F$_7$ to C$_{10}$F$_{21}$. The solid-liquid separations are operationally filtrations and they are easy to manage in parallel settings, either manually or by using various automated techniques. There is no necessity for using flurous solvents when eluting these flurous gels. Different organic solvents are normally used, thus reducing operational costs significantly. Solid-liquid extraction can be operated in cases where molecules have fewer fluorines in the flurous
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tag. This method is currently the most common and easily applied fluorous-organic phase separation technique.

1.7 Fluorous Biphasic Catalysis

The development of environmentally friendly technologies is one of the most demanding targets of modern chemistry and chemical engineering. Environmentally friendly chemical processes should:

- use environmentally safe compounds and solvents;
- have high product yield;
- use efficient reagent or catalyst recycling systems

Acceptance of biphasic liquid-liquid processes, in which a reagent or a catalyst resides in one of the liquid phases and the product moves to the other liquid phase, leads to the commercial applications of many selective reactions. Formation of a liquid-liquid system depends on significantly different intermolecular forces between two liquids. The selection of a catalyst or a reagent mostly depends on the solvent character. The discovery that the miscibility of perfluorocompounds is low with common organic solvents, then lead to the concept of Fluorous Biphasic reactions.

Fluorous Biphasic Catalysis (FBC) was first introduced in 1991, but remained unknown until 1994 when Horváth and Rabáí published their work in Science. Their seminal paper introduced the idea and terms of FBC, concepts that are now well known by chemists. Since then, the concept of FBC has been at the centre of fluorous chemistry. Large amounts of fluorous catalysts and ligands have been synthesized. The defined feature of FBC is the use of two liquid phases: one fluorous, the other organic.
By warming the reaction mixture, the temperature-dependant immiscibility border disappears and the system becomes monophasic, allowing catalysis and thus reaction to happen. By cooling the mixture down, the system returns to two phases and by a simple separation the fluorous catalyst/ligands are separated from organic products. The advantage of this method is the ability of the biphasic system to become monophasic upon heating.

This approach has widely been used in a variety of catalytic reactions as:

- oxidation\(^{31-35}\)
- carbon-carbon bond formation\(^{36,37}\)
- polymerisation\(^{38}\)
- hydrogenation\(^{39,40}\)
- hydroboration\(^{41}\)
- hydroformylation\(^{18,42,43}\)

Studies have focused on fluorous phosphine ligands as the most widely used class of ligands.\(^{43}\) A number of methods has been applied to synthesise fluoroalkyl and fluoroaryl phosphines\(^{44-46}\) employing a variety of spacer groups\(^{47}\) and their operation has been reviewed.\(^{43}\) A number of perfluorophosphines are now commercially available from Fluorous Technologies Inc.\(^{25}\) Numerous fluorous analogues of metal complexes have been prepared and used, including Vaska’s complex analogues:

\[
(\text{trans}-[\text{MCl(CO)L}_2])
\]

\[M = \text{Rh or Ir}; \quad L = \text{P(C}_2\text{H}_4\text{C}_6\text{F}_{13})_3 \text{ or P(C}_6\text{H}_4\text{C}_6\text{F}_{13})_3\]

and Wilkinson’s catalyst analogues:
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RhCl[P(C₂H₄C₆F₁₃)₃]₃

The fluorous-Wilkinson's catalyst has been used for hydroboration reactions of alkenes, initially employing a THF/CF₃C₆F₁₁ biphase. Better yields were obtained using the organic solvent. However, a study using a large number of fluorous analogues found that minimal reduction in rate occurred when moving to a C₆H₄OCH₂-spacer group, thus showing the key importance of the spacer group. In 1994, Horváth illustrated the hydroformylation of 1-octene in 85% yield by using [Rh(CO)₅(acac)] with P(C₂H₄C₆F₁₃)₃ in toluene/perfluoromethylcyclohexane. The experiment also showed the advantage of increased stability of the fluorous catalyst over the organic one in the long-term.

The field has not concentrated solely on phosphines. There exists the possibility to create fluorous analogues of almost any ligands, e.g. the synthesis of a range of bisphosphines, the fluorous analogues of 1,2-bis-diphenylphosphinoethane, has been reported.

The electron density on phosphorus was unaffected by the fluorous tags when a new silicon spacer group was employed.

Alongside fluorous ligands, a variety of reactions using fluorous compounds and solvents has been developed, including alcohol oxidations and epoxidations. An additional character of fluorocarbon solvents is that they dissolve large amounts of molecular oxygen. Betzemein and Knochel have shown that the catalyst generated in situ from the perfluoroalkyl bipyridine 8 (2 mol%), with CuBrMe₂S (2 mol%) and TEMPO (3.5 mol%) in the chlorobenzene/perfluoroctane biphasic system is an outstanding system for the aerobic oxidation of alcohols to aldehydes or ketones.
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The catalyst could be recycled using fluorous solvent and used again for the next eight cycles without losing any activity.

Sheldon\(^5\) has discovered that perfluoroheptadecan-9-one, 9, (5 mol\%) is a mild and selective fluorous-soluble catalyst. It can be used to epoxidise alkenes by hydrogen peroxide. After the process the fluorous solvent with the catalyst can be recovered and reused without decomposition or loss of activity.

There have been number of studies on fluorous-based reduction and hydrogenation methods as well. Millard has used the fluorous ligand\(^5\) 10 with related analogues in the iridium catalysed asymmetric reduction of ketones, using an isopropanol/perfluoroctane biphase.

The same catalyst was used by Pozzi\(^3\) as a fluorous asymmetric epoxidation catalyst. It is fluorous soluble, and when combined with manganese acetate/meta-chloroperbenzoic acid/N-methylmorpholine-N-oxide it catalyses epoxidation reactions in good yields.
Unfortunately, no catalyst recovery method is without its disadvantages. Results, such as those previously described, demonstrated the excellence of the separation method; no catalyst/ligand was detected across the biphase. Chemists, however, claim the high costs of the fluorous solvents and their environmental persistence as the main weakness of the FBC method. In 2001 Gladysz and co workers\textsuperscript{52} reported FBC without the necessity of fluorous solvents. Instead they engineered the melting temperature of the fluorous catalyst to give liquid-liquid separation using an organic solvent. Further steps in this field will be of great benefit for industrial applications of FBC.

1.8 Fluorous Triphasic Reactions

Fluorous triphasic reactions can be explained by two different senses. Pozzi has used a fluorous triphasic system for oxidation reactions by using a triphasic dichloromethane/water/C\textsubscript{8}F\textsubscript{18} reaction medium together with fluorous bipyridine ligands.\textsuperscript{53}

The more accepted triphasic concept has been introduced by Curran. Recently he has completed an innovative experiment using fluorous triphasic system,\textsuperscript{54} but using only fluorous and organic solvents. The three phases included two organic phases divided by a fluorous phase; a U-shaped tube is used to separate a bottom fluorous phase from the upper organic ones.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fluorous_triphase.png}
\caption{Fluorous Triphasic Concept}
\end{figure}

The fluorous phase creates a barrier between two organic phases. Consequently, exchange between the two organic phases can happen only via the fluorous phase. Reactants are loaded in to one organic phase (S) and products are collected from the other organic phase (P). The triphasic system is used here to discharge a fluorous tag from a precursor and at the same time separating detagged product from other products or impurities. Organic reactants and fluorous-tagged compounds are loaded to the phase S and the detagged...
reagent R into the phase P. The fluorous-tagged product moves from the S phase into the F phase to interface with the P phase and detagging takes place. The product then moves into the P phase, since it is no longer soluble in the F phase. As the impurities are not attached to fluorous tags, they always remain in the S phase. The removed tag, because of its high fluorine content, migrates back into the F phase. Many examples of this type of triphasic system have been reported by Curran and his group\textsuperscript{54}. The major advantage of this system over the biphasic one is the lower fluorine content that is required since the molecules only pass through the fluorous phase. Studies of this method are continuing.

1.9 The Need for Fluorous Chemistry

In general, pharmaceutical chemistry can be divided into:

- medicinal chemistry, which includes the discovery of novel lead compounds, their testing and evaluation, and
- process chemistry, which is the development of a synthesis and process for the large-scale synthesis of successful lead compounds.

Using Curran's words\textsuperscript{21}, chemists from both divisions are now 'expected to synthesise everything and quickly'. The most required molecules are small ones, under 600 molecular weight. During the last decade, with the advent of parallel synthesis and combinatorial chemistry, medicinal chemists have improved both the number of molecules they can make and also the speed of the processes. But higher numbers of compounds synthesised in shorter times, need faster methods of purification. Also, process chemists require safe techniques that are cheap and environmentally friendly. The best syntheses are those where products are isolated using simple techniques, like extraction or filtration.

Thus interest in FBC has increased and the advantage of the fluorous process has arisen. It was unavoidable that chemists would soon adopt fluorous techniques in organic synthesis. Since the first example of a fluorous tin hydride being synthesised and used in radical reactions\textsuperscript{55}, many other fluorous reagents have been developed to aid purification and separation.

Our attempted contribution in this field will now be discussed.
Chapter 2

RESULTS & DISCUSSION I: FLUOROUS CHEMISTRY
2.1 Aims

In recent years there has been an explosion of catalytic, environmentally friendly and generally 'green' chemistry. One of the paramount results of this has been the appearance of novel reagents and solvents for use in organic chemistry.\textsuperscript{24}

The group V elements nitrogen and phosphorus are used extensively in synthetic chemistry. Phosphines and organophosphorus reagents are amongst the oldest reagents used by chemists. There are often problems with regard to the toxicity of these reagents and their reaction by-products and also with the difficulty associated with their removal.

Nitrogen containing compounds such as amines and amides are amongst the most utilized reagents in modern chemistry.

Medicinal and process chemists are looking to develop techniques for the rapid synthesis of organo-amines and phosphines and also for their prompt separation and purification.\textsuperscript{17,24}

The present work aims to combine known chemistry with the advantages of fluorous chemistry to provide a new clean technology for the use, handling and purification of organo phosphorus and amine reactions. During the first stage the project focused on aromatic phosphines and later on aliphatic ones; later work switched to organonitrogen compounds and the preparation of an analogue of DEAD. These reagents would be designed to be preferentially soluble in fluorous solvents rather than in organic ones. By using new fluorous techniques, the fluoro-phosphorus and amino compounds synthesised would be used for an investigation of numerous reactions, including the Wittig and Mitsunobu reactions.

Thus our objectives were:

- to develop a new and flexible method for the synthesis of fluorous-containing phosphines, phosphorus-based compounds and fluorous-tagged amines.
- to investigate the potential applications of these fluorinated phosphines and amines in a variety of reactions.
- to investigate the 'cleanness' of these reactions in terms of easy separation and removal of by-products and also for the possibilities of recycling, both of the reagents and solvents.
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2.2 The Wittig Reaction

The Wittig reaction was discovered in 1949 and named after its discoverer, Georg Wittig. It is a reaction between a carbonyl compound (aldehydes or ketones) and a phosphonium ylid. It is possible to divide this process into two parts: first the preparation of a phosphonium salt, then the formation of a phosphorus ylid and its reaction with a carbonyl compound.

2.2.1 Ylids

Ylids are species with positive and negative charges on the adjacent atoms. In phosphonium ylids, the positively charged atom is phosphorus. They can be made from phosphonium salts, which themselves are prepared by the reaction of triphenylphosphine with an alkyl bromide:

\[
\text{Ph}_3\text{P} + \text{CH}_2\text{Br} \rightarrow \text{Ph}_3\text{P} = \text{CH}_2\text{Br}
\]

Scheme 3: Examples and synthesis of phosphonium salts

These are then deprotonated with a strong base such as butyllithium, potassium tert-butoxide or sodium hydroxide to yield the desired ylids.

\[
\text{Ph}_3\text{P} = \text{CH}_2\text{OEt} \rightarrow \text{Ph}_3\text{P} = \text{CH}_2\text{OEt}
\]

Scheme 4: Examples of ylids
There are two kinds of ylids: stabilised and unstabilised ones. In stabilised ylids the negative charge is delocalised by the adjacent functional group, normally by resonance. There is no such effect in the unstabilised ylids. In Figure 9, 14 is a stabilised ylid and 13 an unstabilised one. In general, stabilised ylids give $E$-alkenes in the Wittig reaction and unstabilised ylids $Z$-alkenes.

2.2.2 Mechanism of the Wittig Reaction

One of the main advantages of the Wittig reaction over most other alkene syntheses is that the double bond is created regioselectively, replacing the carbon-oxygen bond of the carbonyl group.

During the first stage, an aldehyde or ketone reacts with the ylid:

\[
\begin{align*}
\text{aldehyde or ketone} & \quad \text{ylide} \\
\begin{array}{c}
\begin{array}{c}
\text{aldehyde or ketone}
\end{array}
\end{array} & \quad \begin{array}{c}
\begin{array}{c}
\text{ylide}
\end{array}
\end{array}
\end{align*}
\]

The ylid, acting as a carbanion, attacks the carbonyl carbon of the aldehyde or ketone. By doing so, it forms an unstable intermediate called a betaine \textit{via} intramolecular nucleophilic attack, which cyclises to form an unstable four-membered cyclic system called an oxaphosphetane. The driving force of the Wittig reaction is the creation of a strong phosphorus-oxygen bond in a molecule of triphenylphosphine oxide 5; the oxaphosphetane loses this part of the system and simultaneously forms an alkene.

\[
\begin{align*}
\begin{array}{c}
\text{oxaphosphetane}
\end{array} & \quad \begin{array}{c}
\text{alkene}
\end{array} & \quad \begin{array}{c}
\text{triphenylphosphine oxide}
\end{array}
\end{align*}
\]

Scheme 5

Scheme 6
Chapter 2: Fluorous Results & Discussion

Recent studies suggest that the oxaphosphetane may be formed directly without the intermediate betaine.56

2.3 Model Wittig Reactions

Before applying any fluorous chemistry to the Wittig reaction, model experiments were carried out on simple substrates.

2.3.1 Stabilised Ylids

One of the starting materials, carboethoxymethyltriphenylphosphorane was prepared58 in two steps. First triphenylphosphine 3 and ethyl bromoacetate were reacted in toluene, to give the target phosphonium salt 15 in 87% yield:

\[
\text{Ph}_3\text{P} + \text{BrCH}_2\text{CO}_2\text{Et} \xrightarrow{\text{toluene}} \text{Ph}_3\text{PCH}_2\text{CO}_2\text{Et} \cdot \text{Br}
\]

Scheme 7

This was deprotonated by adding slowly a solution of 0.1 M sodium hydroxide. After crystallisation, the target ylid 16 was isolated in 58% yield:

\[
\text{Ph}_3\text{PCH}_2\text{CO}_2\text{Et} \cdot \text{Br} \xrightarrow{\text{NaOH}} \text{Ph}_3\text{PCHCO}_2\text{Et}
\]

Scheme 8

This is termed a stabilised ylid since the negative charge in the phosphorus ylid is stabilised by a resonance effect:
Reaction with phenylacetaldehyde gave the trans (E) isomer of the alkene, proved by NMR spectroscopy, from the observed olefinic coupling constant of 15.9 Hz. The final alkene 17 was isolated in 60% yield, with no trace by NMR of the Z-isomer.

\[
\begin{align*}
\text{Ph}_2\text{C}^\equiv\text{O} + \text{Ph}_2\text{P}^- &\overset{\text{DCM}}{\rightarrow} \text{H} \text{C}^\equiv\text{C} \text{O}^- \text{Et} \\
\end{align*}
\]

Scheme 10

2.3.2 Unstabilized Ylids

A similar reaction sequence was performed using an unstabilised ylid. Starting from triphenylphosphine 3 and 1-bromobutane, butyltriphenylposphonium bromide 18 was first obtained in 26% yield:

\[
\begin{align*}
\text{Ph}_2\text{P}^- + \text{BrCH}_2\text{CH}_2\text{CH}_3 &\rightarrow \text{Ph}_3\text{PCH}_2\text{CH}_2\text{CH}_3 \text{ Br} \\
3 &\rightarrow 18
\end{align*}
\]

Scheme 11

This was then reacted with potassium tert-butoxide in dry tetrahydrofuran, followed by 2,4-dichlorobenzaldehyde. Finally, the required product 19 was isolated in 52% yield.

\[
\begin{align*}
\text{Ph}_3\text{PCH}_2\text{CH}_2\text{CH}_3 \text{ Br} &\overset{\text{KOBu}^+}{\rightarrow} \text{Cl} \text{C} \equiv \text{C} \text{(CH}_2\text{CH}_3) \\
18 &\rightarrow 19
\end{align*}
\]

Scheme 12

Knowing that these model systems were successful and reproducible, the next stage was the synthesis of fluorous analogues of triphenylphosphine and then to repeat the Wittig chemistry using this fluorinated triphenylphosphine.
2.4 Fluorous phosphines for the Wittig Reaction

As mentioned above, the first target was a preparation of fluorous-tagged phosphines. After some literature observations was selected the analogue of triphenylphosphine, \( \text{tris}(4\text{-tridecafluorohexylphenyl}) \) phosphine 4, a suitable compound for future studies:

\[
\begin{align*}
\text{C}_5\text{F}_{13} & \quad \text{FF} \quad \text{FF} \quad \text{FF} \quad \text{PP} \\
\text{FF} & \quad \text{FF} \quad \text{FF} \quad \text{FF} \\
\text{FF} & \quad \text{FF} \quad \text{FF} \quad \text{FF} \\
\text{FF} & \quad \text{FF} \quad \text{FF} \quad \text{FF} \\
\text{FF} & \quad \text{FF} \quad \text{FF} \quad \text{FF} \\
\text{FF} & \quad \text{FF} \quad \text{FF} \quad \text{FF} \\
\end{align*}
\]

To obtain this compound, several routes were explored. The first can be divided into two parts:

1. preparation of 4-(tridecafluorohexyl)bromobenzene 22
2. preparation of \( \text{tris}(4\text{-tridecafluorohexylphenyl}) \) phosphine 4.

The literature method of Hope et al. was attempted for the preparation of 4-(tridecafluorohexyl)bromobenzene 22. A solution of iodoperfluorohexane (1 eq) in hexafluorobenzene was added dropwise over 3 h to a stirred mixture of 4-bromoiodobenzene 21 (1 eq), copper powder (2.2 eq), 2,2'-bipyridine (0.07 eq), DMSO and hexafluorobenzene at 70°C.

\[
\begin{align*}
\text{C}_5\text{F}_{13} & \quad \text{Br} \\
\text{Br} & \quad \text{Br} \\
\end{align*}
\]

This reaction was repeated several times on different scales, following exactly the procedure described in the literature. Unfortunately, none of the desired compound 22 was obtained. A slight modification of the procedure suggested by Professor Hope was also attempted, but with little success. In place of the desired product, an inseparable mixture of products was obtained. Based on GC-MS analysis of this mixture, it is believed that the
three principle products formed in the reactions are the desired product 22, along with the iodo-form of this compound (from exchange of the bromine rather than the iodine) and the bis-coupled product.

The procedure was repeated using both an excess of copper powder and also activating the copper powder prior to reaction. The powder was activated by washing rapidly with a weak solution of hydrochloric acid (1 M), washed with large quantities of distilled water to remove all traces of the acid, then washed with acetone to remove water and finally washed with diethyl ether. It was dried under vacuum then stored under nitrogen. After this, the experiment was repeated five times using the freshly activated copper powder in varying levels of excess (2.5 eq, 2.8 eq, 3 eq, 4 eq and 5 eq). In all cases no pure sample was isolated. Neither $^{19}$F or $^{13}$C NMR proved helpful in assessing the purity of the mixture. Unfortunately, no pure sample of 22 could ever be obtained, irrespective of the method of purification attempted (distillation or chromatography).

In an attempt to obtain a sample of the fluorous-phosphine analogue to test the Wittig reactions, it was decided to take the mixture of compounds on to the second step in the synthesis, in the hope that both the bromo- and iodo-compounds would react with PCl$_3$ to give the desired product and that it would be possible at this stage to separate the desired product from the bis-fluorous coupled compound. Consequently, the pale yellow solution from the first stage was reacted with n-butyllithium (1 eq.) in THF at -78°C, followed by freshly distilled phosphorus trichloride (1/3 eq.) at -78°C.$^{44}$
This reaction was largely unsuccessful, possibly due to the mixture of starting materials employed and not knowing the exact molar equivalences to employ. After each successive attempt, however, small quantities (10-15% yield) of the desired product, 4, were obtained, suggesting that if a better method for the preparation of 22 could be found then this second step may well be useful. The amount of time and effort required to obtain 4, though, made this route not practical at this stage.

Therefore it was decided to investigate alternative routes to 4. One proposed method was to look at the direct introduction of the fluorous chain into tris(4-bromophenyl)phosphine 23. This was prepared using the same method as described above for the coupling of aromatic halides with PCl₃. Reaction of 21 with n-butyllithium followed by PCl₃ consistently gave high yields (>70%) of the desired tris(4-bromophenyl)phosphine 23, irrespective of the reaction scale and the procedure could be repeated on scales up to 20 g.

The same method was then applied to couple the fluorous chain to 23, using activated copper power and the same molar quantities as in the original publication.

Again, the experiment was performed several times on different scales and using both activated and non-activated copper powder, but no 4 was obtained; on some occasions starting materials were recovered and on others no identifiable material was obtained at all.
Therefore, a third method was envisaged, which would involve formation of the phosphine oxide 6, which would then be reduced to 4.\(^5^9\)

![Diagram](image1.png)

Scheme 17

The idea behind this route was that the lone pair of electrons on phosphorus may be interfering with the copper-coupling process. Therefore, if these electrons could be 'locked up', or protected, the coupling may proceed in better yields and the phosphorus could be deprotected at a later stage (although unfortunately, this would add an extra couple of steps to the synthesis of 4).

First, a test reaction was performed using commercially available \(\text{tris}(4\text{-chlorophenyl})\) phosphine 25. Oxidation was achieved using 30% hydrogen peroxide solution (in excess) to give 26 in near-quantitative yield.\(^5^9\) This was then reacted with trichlorosilane (5 eq) and triethylamine (7.5 eq) at reflux\(^4^5\) to give the reduced phosphine 25, albeit in only low yield (20%). A second method, using polymethylhydrosiloxane and titanium (IV) isopropoxide\(^6^0\) was attempted; This consistently gave much better yields than the first method for the reduction. Therefore this became the method of choice for the reduction of phosphine oxides.

![Diagram](image2.png)

Scheme 18

As it was readily available from commercial material, it was decided to react 26 with \(\text{C}_{6}\text{F}_{13}\) under the copper-promoted conditions. Only starting material was recovered.\(^4^5\)
Therefore attention returned to the tris4-bromotriphenylphosphine, 23. This was readily oxidised to the phosphine oxide 27 in excellent yield.

\[
\begin{align*}
23 & \rightarrow 27 \\
\text{Scheme 19}
\end{align*}
\]

With 27 isolated, it was again tested under both sets of conditions for reduction to obtain a phosphine. Again, the first using trichlorosilane (5 eq) and triethylamine (7.5 eq) at reflux temperature was poor, while the second using titanium (IV) catalysis involving (polymethylhydrosiloxane (PMHS) (10 eq) and titanium (IV) isopropoxide (1 eq) was much more successful and gave the desired product (73%).

After observations at a Conference (R.S.C. Annual Congress, Birmingham 2001) and discussions (Professor Dennis Curran, University of Pittsburgh), it was suggested to use fluorous compounds with an organic spacer group between the aromatic ring and the fluorous chain, as this may be easier to prepare. Thus tris(4-1H,1H,2H,2H-tridecafluorooctyl)phosphine 28 was targeted. It was suggested that this should be obtained.
using tris(4-bromophenyl)phosphine 23 and 1H,1H,2H,2H-tridecafluorooctyl iodide, using conditions adopted from above using copper.  

![Chemical structure](image)

Unfortunately none of the specified compound was isolated, so an identical reaction was carried out with the previously prepared bromosubstituted phosphine oxide 27

![Scheme 22](image)

Again, these experiments were carried out several times, using different scales and conditions, but with no product being obtained. An interesting observation, however, which had been noticed before but only in passing, was the homo-coupling of starting materials. During all these experiments there was a potential problem of binding two different molecules by substituting existing halogens. In this latest experiment in particular, dimerisation of the 1H,1H,2H,2H-tridecafluorooctyl iodide was observed as the major reaction product. Re-examination of previous reaction mixtures, which had not necessarily been separated, also showed the presence of dimerisation products, particularly from the fluorous halide, but also with the suggestion of biphenyls as well.

Therefore as an alternative, it was decided to look at a non-halogen-based starting material. It was proposed to make an ether-linked fluorous phosphine, 30. Tris(4-methoxyphenyl)phosphine 31 is commercially available and is readily oxidised with hydrogen peroxide, as before, to the phosphine oxide in quantitative yield.
Chapter 2: Fluorous Results & Discussion

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Scheme 23

The demethylation reaction[^1], to obtain tris(hydroxyphenyl)phosphine oxide 32, is a known literature procedure using boron tribromide. However, none of the desired compound was obtained and no identifiable material could be recovered.

![Scheme 23](image)

Scheme 24

In a final attempt to obtain a fluorous-soluble triphenylphosphine analogue, a completely new approach was taken, and instead of trying to add a fluorous chain to an aromatic compound, the fluorines were to be placed directly on the aromatic ring. Commercially available iodopentafluorobenzene was readily transformed into tris(pentafluorophenyl)phosphine 33 using standard lithium-halogen exchange with n-butyllithium.[^44]

![Scheme 24](image)

Scheme 25

This was then reacted with bromoethylacetate (1 eq) to form the precursor for a stabilised ylid.

![Scheme 25](image)

Scheme 26
Although this reaction gave the mixture of fluorine contained substances (67%), unfortunately the tris-pentafluorophenylphosphine showed no selective solubility for the fluorous phase over an organic solvent, distributing itself almost equally in test separations. In hindsight, this is hardly surprising since the compound does not possess the pre-requisite minimum 60% fluorine, which is normally suggested as minimum fluorine content required to impart selective fluorous solubility.

**Scheme 27** summarises all the routes attempted to prepare fluorous phosphines.

![Scheme 27](image)

\[ F = C_{6}H_{5}F_{13} \text{ or } CH_{2}CH_{2}C_{6}H_{5}F_{13} \]

It was at this point that a publication from Sinou reported the first examples of a fluorous-based Wittig reaction. Thus, given the problems encountered preparing the fluorous phosphines and also the appearance in the literature of a related study, it was decided to abandon this line of research and to look at an alternative fluorous-based reagent.
2.5 The Mitsunobu Reaction

The condensation reaction of an alcohol with an acidic Nu-H containing nucleophile, using the redox couple of a trialkyl or triaryl phosphine and a dialkyl azodicarboxylate, is known as the Mitsunobu reaction. It is a second reaction that often has associated purification problems, but one that has became very popular in recent years and gives excellent yields of reaction products, although the two by-products in the reaction can often be problematic to remove. The reaction has been extensively reviewed and may be summarized:

\[
\begin{align*}
R^1OH & \quad H-Nu & \quad PPh_3 & \quad RO_2CN=NCO_2R \\
\downarrow & & & \\
R^1\text{-Nu} & \quad Ph_3P=O & \quad RO_2CN=NCO_2R
\end{align*}
\]

Scheme 28

An alcohol (R\(^1\)OH) and an acidic component (H-Nu) are condensed to form the product (R\(^1\)-Nu), while triphenylphosphine is oxidised to triphenylphosphine oxide and the dialkyl azodicarboxylate is reduced to the hydrazine. Diethyl azodicarboxylate (DEAD) is the usual carboxylate of choice, along with triphenylphosphine, although other combinations are known.\(^{18,19}\)

As in case of the Wittig reaction, the driving force of the Mitsunobu reaction is the formation of a strong phosphorus-oxygen bond. The reaction is most commonly employed for the direct replacement of a hydroxyl group by a nucleophile.

The reaction is a redox couple, the phosphine bonds with the oxygen of an alcohol, while the azodicarboxylate accepts hydrogen to end with the corresponding hydrazine derivative. The reaction gives good yields (60-90%) and proceeds well with primary and secondary alcohols.\(^{63}\)
2.5.1 Mechanism

In the first step, the lone pair of electrons of phosphorus from triphenylphosphine attack one of the nitrogen atoms of DEAD:

![Scheme 29]

Stabilisation of the nitrogen anion happens by delocalisation onto the adjacent oxygen atom of the carbonyl group. The nucleophile must possess an acidic H atom. The pH should generally be less than 13. Next, the nucleophilic agent reacts.

![Scheme 30]

Examples of nucleophilic regents which can be used are carboxylic acids, thioacids, phenols, thiols, imides, sulfonamides, heterocyclic compounds, hydrogen halides, phosphine diesters, phosphonic acids and certain active methylene compounds.

The lone pair of electrons of the oxygen of the hydroxyl group then attack the positively charged phosphorus atom:

![Scheme 31]
In the final stage, the negatively charged nucleophile formed in Scheme 30 now attacks the R group from the phosphonium salt in an $S_n2$ manner and the phosphorous-oxygen double bond forms by finally breaking the O-R bond.

\[
\begin{align*}
\text{Ph}_3\text{P}^+\text{N}^\text{+} & \quad \text{Nu} \\
\text{Ph}_3\text{P}=\text{O} & \quad \text{R} \\
\text{Ph}_3\text{P}^+\text{N}^\text{+} \quad \text{Nu} & \quad \text{R} \quad \text{Ph}_3\text{P}=\text{O} \\
\end{align*}
\]

Scheme 32

Studies$^{65}$ have shown that without acidic components, $N$-alkylhydrazinedicarboxylates can be formed, Scheme 33:

![Scheme 33](image)

2.5.2 Stereochemistry

The Mitsunobu reaction is a highly stereospecific reaction; one of its major uses is that with optically active substrates, it proceeds with complete inversion of configuration. Since the final step of the mechanism involves an $S_n2$ reaction, then the overall outcome of the reaction must be that it proceeds with inversion of configuration. For example, in an esterification reaction involving a chiral alcohol, the ester is formed with inversion of configuration.$^{64}$

![Scheme 34](image)

2.5.3 Order of Addition

Of paramount importance in the Mitsunobu reaction is the order of addition of the various components. Normally non-polar solvents are used as they increase significantly the speed of the reaction. Generally, in the first step, the alcohol, acid and
triphenylphosphine are dissolved in the solvent, usually THF, and cooled to 0 °C. Then the DEAD is added slowly and the reaction left stirring at room temperature for several hours.\(^\text{54}\)

### 2.6 Fluorous Mitsunobu Reaction

A common problem of the Mitsunobu reaction is the separation of the product from triphenylphosphine oxide and the hydrazine. In conjunction with the preparation of fluororousphosphines for use in the Wittig reaction, it was envisaged that the same phosphines could be utilised in a fluorous version of the Mitsunobu reaction.\(^\text{66}\) However, for a fully-fluorous version of the reaction, it would also be necessary to prepare a fluorous version of DEAD, abbreviated \(^F\)DEAD. Although, as previously reported, an effort to prepare fluorousphosphines was unsuccessful, attempts at \(^F\)DEAD were more successful and promised to provide a partially-fluorous Mitsunobu reaction.

#### 2.6.1 Retrosynthesis of \(^F\)DEAD

Just as other fluorous reagents have been designed, an alternative to DEAD must be a possible solution to the problem of purifying the Mitsunobu reaction.\(^\text{66}\) The aim of this work is to prepare a fluorous analogue of an azodicarboxylate which will react in the Mitsunobu reaction in the same manner as the traditional counterpart, but that can be removed from a reaction mixture using fluorous separation techniques. The proposed version contains large fluorocarbon chains to ensure selective fluorous solubility and also a \(-\text{CH}_2\text{CH}_2-\) spacer group to shield the reaction centre from the fluorous chains. The proposed compound also contains greater than the 60% threshold for selective fluorous solubility. The retrosynthetic approach to \(^F\)DEAD is presented in Scheme 35.
2.6.2 Synthesis of $^F$DEAD$^{56}$

Commercially available $1H,1H,2H,2H$-perfluoro-$1$-octanol 34 was employed as a readily available starting material. This was easily transformed to the corresponding fluorous chloroformate 35 by slow addition to a 20% solution of phosgene in toluene at 0 °C. The reaction was initially performed using 1 equivalent of phosgene, but some starting material always remained. The use of 1.5 equivalents, however, forced the reaction to completion and remaining traces of phosgene could be removed by rotary evaporation. (Safety precautions were taken throughout when handling phosgene). The fluorous chloroformate 35 was isolated as a pale oil which could be used immediately without further purification.

The fluorous hydrazine 36 was easily formed by reaction of the fluorous chloroformate 35 with hydrazine hydrate in the presence of sodium carbonate in ethanol. Maintaining a constant temperature of 0 °C was important to achieve a high yield. After the addition the mixture was stirred at room temperature for 2 h and after filtration and re-crystallisation from ethanol, the product was obtained as white crystals in 81% yield over the 2 steps. The fluorous hydrazine 36 could be stored easily and without decomposition.
The final stage involved oxidation of the hydrazine 36 to form the N=N function of the target molecule. Initially, lead tetraacetate was attempted, with little success. Two different oxidants, N-bromosuccinimide\textsuperscript{66} and molecular bromine were utilised for this transformation. Of these, freshly recrystallised NBS was generally the more successful oxidant, with the product 37 being obtained in 92\% yield.

\begin{equation}
\begin{array}{c}
\text{F}_3\text{C}_6^\text{O} \text{C} \text{N}^\text{N} \text{O} \text{C} \text{F}_{13}^\text{C}_6^\text{O} \\
\end{array}
\end{equation}

Scheme 37

2.7 Partition Coefficients

To determine which solvent combinations were best for liquid-liquid fluorous extractions (of the fluorous hydrazine by product from organic solvents), it was decided to determine the partition coefficients of both the fluorous hydrazine and \textsuperscript{7}DEAD for a range of solvent combinations.

Partition coefficients were determined using two different methods.\textsuperscript{67} The hydrazine or \textsuperscript{7}DEAD was stirred in different combinations of fluorous and organic solvents for 22 h at 22 °C and then allowed to stand for one hour. The two layers were then separated and each layer analysed against a reference of dodecane in hexane using gas chromatography. Seven injections were made of each sample and an average of the integrations taken. These were then used to calculate the ratio of hydrazine or \textsuperscript{7}DEAD in each layer. While reliable for the fluorous hydrazine, \textsuperscript{7}DEAD was not entirely stable to gas chromatography and inconsistent results were obtained. Therefore an alternative accurate weighing method was employed.
The remainder of the two layers were then separately evaporated and the mass of hydrazine or $^5$DEAD found in each layer recorded and used to calculate the ratio in each layer. The ratios obtained by this method were identical to the ones obtained via the GC method. The results are presented in Table 4.

**Table 4: Partition coefficients for fluorous hydrazine and $^5$DEAD**

<table>
<thead>
<tr>
<th></th>
<th>Fluorous hydrazine</th>
<th>Fluorous DEAD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FC-72</td>
<td>Perfluoromethyl-cyclohexane</td>
</tr>
<tr>
<td>THF</td>
<td>99.3:0.7</td>
<td>98.1:1.9</td>
</tr>
<tr>
<td>Toluene</td>
<td>64.1:35.9</td>
<td>84.8:15.1</td>
</tr>
<tr>
<td>DCM</td>
<td>81.0:19.0</td>
<td>51.0:49.0</td>
</tr>
<tr>
<td>Methanol</td>
<td>95.4:4.5</td>
<td>99.6:0.5</td>
</tr>
<tr>
<td>Methanol (80%)</td>
<td>70.7:29.3</td>
<td>100.0:0.0</td>
</tr>
</tbody>
</table>

The values obtained for the fluorous hydrazine would be most important, since it would be this compound, as one of the main Mitsunobu reaction by-products, that would need to be separated by fluorous liquid-liquid extraction. The values obtained would suggest that THF and methanol would be the most suitable solvents to employ, since very high levels of selectivity were observed for the fluorous hydrazine in the fluorous solvent, rather than partitioning between the two phases.

**2.8 Mitsunobu Reactions**

After successfully synthesising $^5$DEAD, reactions had to be performed to test that it did indeed work as well as traditional DEAD in the Mitsunobu reaction.
2.8.1 Model Mitsunobu Reactions Employing DEAD

A set of Mitsunobu reactions were run using traditional reagents and reaction conditions, as illustrated in Table 5.

Table 5: Test Mitsunobu Reactions

<table>
<thead>
<tr>
<th>Entry</th>
<th>ACID</th>
<th>ALCOHOL</th>
<th>DEAD+PPh₃ % YIELD</th>
<th>DEAD+S-S-PPh₃ % YIELD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image" alt="Phenylacetic Acid" /></td>
<td>Et-Oh</td>
<td>85</td>
<td>52</td>
</tr>
<tr>
<td>2</td>
<td><img src="image" alt="Benzoic Acid" /></td>
<td>Me-Oh</td>
<td>78</td>
<td>43</td>
</tr>
<tr>
<td>3</td>
<td><img src="image" alt="Hydroxychlorobenzene" /></td>
<td>Ph-OH</td>
<td>81</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td><img src="image" alt="Benzoic Acid" /></td>
<td>Me-Oh</td>
<td>92</td>
<td>Not performed</td>
</tr>
</tbody>
</table>

All the Mitsunobu reactions proceeded in high yield, to give the desired products that were easily purified by chromatography. The Mitsunobu reactions were also run with solid-supported (S-S) triphenylphosphine. It was hoped that this would be a useful alternative for triphenylphosphine, giving cleaner separation, but also that it could later be coupled with \(^\text{FDEAD}\) to give a Mitsunobu reaction that could be easily purified by filtration and extraction. Unfortunately, the yields for the reactions with solid-supported triphenylphosphine were much lower than expected. It is thought that this is primarily due to the quality of the phosphine; this was found to contain approximately 30% triphenylphosphine oxide upon purchase.
2.8.2 Mitsunobu Reactions Employing $^f$DEAD

The identical Mitsunobu reactions from Table 5 were performed, but this time using freshly prepared $^f$DEAD. As Table 6 shows, comparable yields were obtained. All the reactions proceeded in the same manner as the traditional Mitsunobu reactions, but instead of the need for column chromatography, the reactions were purified using liquid-liquid fluorous extraction. The best combinations were found to be THF and FC-72 or perfluoromethylcyclohexane, although other solvent systems were tested. It was found that 2 or 3 extractions were required to remove all traces of the fluorous hydrazine. This combination is hardly surprising, given the favourable partition coefficients previously described.

Table 6: Mitsunobu Reactions Employing $^f$DEAD

<table>
<thead>
<tr>
<th>ACID</th>
<th>ALCOHOL</th>
<th>$^f$DEAD+PPh$_3$ % YIELD</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Ph$_3$COOH" /></td>
<td>Et-OH</td>
<td>84</td>
</tr>
<tr>
<td><img src="image" alt="Ph$_3$COOH" /></td>
<td><img src="image" alt="Ph$_3$COOH" /></td>
<td>73</td>
</tr>
<tr>
<td><img src="image" alt="Ph$_3$COOH" /></td>
<td><img src="image" alt="Ph$_3$COOH" /></td>
<td>78</td>
</tr>
<tr>
<td><img src="image" alt="Ph$_3$COOH" /></td>
<td><img src="image" alt="Ph$_3$COOH" /></td>
<td>91</td>
</tr>
</tbody>
</table>

Thus it has been shown that $^f$DEAD is a viable alternative to DEAD in the Mitsunobu reaction and gives good reaction conversions and easy product separations. Unfortunately, as we could not prepare the fluorous phosphines, it was impossible to prepare a fully
fluorous version of the Mitsunobu reaction, although this has since been reported by Curran.\textsuperscript{17,21}

2.9 Alternative Uses of DEAD

2.9.1 Amination Reactions

A second reaction in which DEAD has been widely employed is the amination of aromatic compounds: coupling of an aromatic compound with DEAD in the presence of a catalyst gives an aromatic hydrazine, which may then be reduced to the aniline.\textsuperscript{68,69} Potentially, the use of $^F$DEAD in these reactions would lead to a much simpler method for the purification of the aromatic hydrazine intermediate prior to the reduction step. Therefore it was decided to use our $^F$DEAD in this context, but first, again, it was necessary to perform some model reactions.

2.9.2 Conventional Method\textsuperscript{68}

Traditionally, amination reactions of aromatics using DEAD require long reaction times and high temperatures. As well as attempting this method, a second method using microwave irradiation was also tested. Both methods used a mixed indium trichloride and silicon dioxide catalyst.

A mixture of 1,3,5-trimethoxybenzene 38 (1 eq), DEAD (1 eq) and freshly prepared catalyst\textsuperscript{58} (0.1 eq) in dichloroethane was stirred at reflux temperature for 10 h. After the work up the crude product 39 was found in high yield (>90%) and almost clean by NMR spectroscopy. Since this was only a test reaction, this compound was not fully purified.

\begin{center}
\textbf{Scheme 39}
\end{center}
Freshly obtained 1,3,5-trimetoxy-2-diethylaminodicarboxylate 39 was reacted in crude form with freshly activated zinc in glacial acetic acid to obtain the amino product 40. The experiment was run several times with only modest yields of product (35-48%) being obtained.

![Scheme 40](image)

The identical reactions were then repeated using ^F DEAD instead of normal DEAD, but the reaction failed, with only 1,3,5-trimethoxybenzene being recovered.

![Scheme 41](image)

The same reactions were repeated using 1-methoxybenzene 41 and naphthalene 42. The first reaction with 41 gave a product in a good yield (71%), whereas after the reaction with naphtaleene the starting material being recovered.

![Scheme 42](image)
2.9.3 Microwave Irradiation

An alternative method of heating that was employed was that of microwave irradiation; this has considerable attraction and advantages over conventional heating methods, particularly with respect to greatly reduced reaction times. The experiments were carried out in few minutes compared to conventional overnight reactions. Various conditions were tested for each experiment and the results summarised in Table 7.

Table 7: Amination Reactions performed in the microwave.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Solvent</th>
<th>Power /Watts</th>
<th>Pressure in psi</th>
<th>Temperature</th>
<th>Time /mins</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>300</td>
<td>7</td>
<td>100</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>300</td>
<td>7</td>
<td>200</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>300</td>
<td>7</td>
<td>150</td>
<td>5</td>
<td>69</td>
</tr>
<tr>
<td>4</td>
<td>1,2-</td>
<td>300</td>
<td>7</td>
<td>150</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>dichloroethane</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>THF</td>
<td>300</td>
<td>7</td>
<td>150</td>
<td>7</td>
<td>61</td>
</tr>
<tr>
<td>6</td>
<td>THF</td>
<td>300</td>
<td>7</td>
<td>180</td>
<td>7</td>
<td>68</td>
</tr>
<tr>
<td>7</td>
<td>THF</td>
<td>300</td>
<td>7</td>
<td>160</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>1,2-</td>
<td>300</td>
<td>7</td>
<td>165</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>dichloroethane</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>THF</td>
<td>300</td>
<td>7</td>
<td>160</td>
<td>8</td>
<td>71 (para)</td>
</tr>
<tr>
<td>10</td>
<td>THF</td>
<td>300</td>
<td>7</td>
<td>130</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>THF</td>
<td>300</td>
<td>7</td>
<td>160</td>
<td>8</td>
<td>-</td>
</tr>
</tbody>
</table>
The results show the critical nature of the reaction conditions employed, although it is interesting to note that naphthalene (entries 10 and 11) failed to give any products under both conventional and microwave heating, despite literature reports to the contrary. From entries 5, 6 and 9, it would appear that THF is the solvent of choice for these microwave reactions. Anisole also worked well under microwave irradiation conditions, giving 71% of the para-substituted product, with just a trace (<3%) of the other possible isomers.

Therefore the favoured conditions of entries 3, 6 and 9 were attempted using ^DEAD. The solvent-free reaction rapidly darkened and no products could be isolated or identified. In THF as solvent, however, under the conditions of entry 6, both anisole and 1,3,5-trimethoxybenzene gave reasonable yields of the fluorous-hydrazine (65 and 58% respectively). Water was added to the THF and the solution extracted with FC-72 and perfluoromethylcyclohexane and evaporated to give these yields. No other purification was performed. Although partition coefficients were not recorded, both compounds had high levels of fluorous solubility and no residual fluorine-containing compounds were found (by ^19F NMR) in the aqueous layer (when extracted with ethyl acetate and evaporated).

Unfortunately, the cleavage of the hydrazine with Zn/AcOH was unsuccessful and time prevented a full investigation of reaction conditions and alternatives to achieve this transformation.
2.10 Conclusions

The original plan had been to prepare fluorous analogues of various phosphines and also DEAD. While the work on the fluorous phosphines was unsuccessful, the studies to prepare a fluorous version of DEAD were successful and this reagent has been successfully applied to the Mitsunobu reaction and, to a lesser extent, to some microwave-based amination reactions.

Attention will now turn to a different area of fluorine chemistry.
Chapter 3

INTRODUCTION TO HETEROCYCLES
Chapter 3: Introduction to Heterocycles

3. Oxygen heterocycle-containing natural products

Tetrahydropyrans and dihydropyrans are important units in many natural products and synthetic molecules.

3.1. Tetrahydropyrans

Tetrahydropyrans are the backbones of most carbohydrates and their polymers. These materials are the most abundant biological molecules on earth and play several crucial roles in living organisms. They are found in the cell walls and protective coatings of many organisms and also fuel various metabolic processes.

* cis-(6-methyltetrahydropyran-2-yl)acetic acid 43 possesses a cis-2,6-disubstituted tetrahydropyran core. It is one of the most important components isolated from *Viverra civetta* and it has long been used as a fixative in the perfume industry.

![cis-6-(Methyltetrahydropyran-2-yl)acetic acid](image)

Various polyethers have been previously isolated from marine sources and their most notable features are the cyclic ethers rings of various sizes. Some of these polycyclic compounds which show diverse biological activities, include ciguatoxins, brevetoxins (neurotoxics), gambierol (used for stomach and lung disease testing), and yessotoxin (controls body weight).

3.2. Dihydropyrans

Penitrem D (44, Fig. 7) belongs to an important family of environmental toxins, produced by ergot fungi that grow on a variety of grasses endemic to South Africa, New Zealand and the United States. It is a polycyclic molecule that includes a 2,3,5,6-
tetrasubstituted dihydropyran skeleton and a substituted eight-membered oxygen containing system.

Penostatin D 45 is a tricyclic biactive secondary metabolite produced by Penicillium sp. and exhibits significant cytotoxic activity in the P388 lymphocytic leukemia test systems in cell cultures. A long unsaturated alkyl chain is incorporated in the C-2 position of the dihydropyran unit.

Laulimalide 46 is a potent microtubule-stabilising anticancer agent isolated from the Pacific sponges Hyatella sp. and Spongia mycofijiensis and the Okinawan sponge Fasciospongia rimosa. It is a macrolactone containing 2,6- and 4,6-disubstituted dihydropyran units. Nodulisporic acid A (NAA) 47 is a polycyclic molecule featuring a 2,4,5,6-tetrasubstituted dihydropyran ring system. It is an indole-diterpene metabolite produced by Nodulisporium sp., an endophytic fungus isolated from a woody plant and it exhibits potent insecticidal activities.

---

![Figure 7](image-url)

**Fig. 7**
3.3. The combination of tetrahydropyrans and dihydropyrans

The combination of tetrahydropyrans and dihydropyrans is also a common structural feature of many natural products.

Okadaic acid (48, Fig. 8) is the causative agent of diarrhetic shellfish poisoning. It was initially isolated from two marine sponges *Halichondria okadaii* and *H. melanodocia* but later found to come from certain varieties of marine plankton and to accumulate in sponges. It contains a 2,4,6-trisubstituted dihydropyran ring system and two spiroketal units, as well as a fused six-membered oxygenated ring system.

Ambruticin 49 was isolated from fermentation extracts of the Mycobacteria species *Polyangium cellulosum* var. *fulvum* and is an orally active antifungal agent showing *in vitro* and *in vivo* activity against a variety of pathogenic fungi. This molecule incorporates a 2,3,6-substituted dihydropyran system and a substituted tetrahydropyran ring system which are connected via a long unsaturated alkyl chain.

Martiriol 50 is a new cytotoxic compound featuring fused six-membered oxygenated rings, a 2,6-disubstituted dihydropyran ring containing a long alkyl chain in the C-2 position and a substituted tetrahydropyran ring. It was isolated as a secondary metabolite of red algae of the genus *Laurencia*.79

---

Fig. 8
The natural marine products Swinholides 51, 52 and 53 (Fig. 9), isolated from the Okinawan marine sponge *Theonella swinhoei*, exhibit potent cytotoxicity against a variety of human carcinoma cell lines, as well as a broad spectrum of antifungal activity.\(^{80-84}\) Swinholides are macrolactones containing 2,6-disubstituted and 2,4,6-trisubstituted dihydropyran type structures interconnected by long polysubstituted alkyl chains.

**Fig. 9**

### 3.4 Methods for the Preparation of 5,6-dihydro-2H-pyrans

Having discussed the common dihydropyran skeleton of many natural products a short summary of the main methods for their preparation will be outlined.

#### 3.4.1 Introduction

The oxa-analogues of cyclohexene related to 2H-pyran 54 include 5,6-dihydro-2H-pyran 55 (Fig. 10).\(^{85}\)
3.4.2. [4+2] Cycloaddition reactions

[4+2] Cycloaddition reactions, especially the Diels-Alder and hetero-Diels-Alder reactions, are the concerted reactions of $4\pi$ and $2\pi$ components to give a cyclohexene ring. Cycloaddition reactions are widely used synthetic methodologies for the regio- and stereoselective construction of 5,6-dihydro-2H-pyran structures. The selectivities of the hetero-Diels-Alder reactions are not always high and considerable attention has been paid to developing new catalysts for improving the reaction.

Recently, the hetero-Diels-Alder approach has been used in the total synthesis of various natural products. Jacobsen's group has developed chiral chromium based catalysts 56 and 57 for hetero-Diels-Alder reactions and utilised them during the key step in the total synthesis of FR901464, 58, the most potent member of a new series of bacterially produced antitumour antibiotics (Scheme 44).
3.4.3. Ring Closing Metathesis

Ring closing metathesis is the transition metal catalysed cyclisation reaction in which two remote alkene parts of a molecule are brought together to form the ring system. Since the development of new ruthenium-based catalysts by Grubbs\textsuperscript{95-97} and molybdenum-based catalysts by Schrock,\textsuperscript{98,99} ring closing metathesis has become an important and widely used synthetic tool for the construction of many heterocycles, including 5,6-dihydro-2H-pyrans. Numerous examples of synthetic routes towards dihydropyrans based on ring closing metathesis are given in the literature.\textsuperscript{100-105}

Rutjes and co-workers have developed a method based on ring closing metathesis for the synthesis of functionalised dihydropyrrans 59 and tetrahydrooxepines 60 and 61 (Scheme 45).\textsuperscript{106}
3.4.4. Condensation reactions

Condensation reactions are those in which two molecules combine with loss of a small molecule, often water. Condensation reactions of silyl acetals 63 and various aldehydes in the presence of Lewis acids were found to give good yields of chlorinated dihydropyran 64 (Scheme 46).\(^ {112} \)

It has also been reported that in the presence of Lewis acids, acyclic diesters terminated by a vinylsilane moiety 65 lead to dihydropyran building blocks 66 (Scheme 47).\(^ {113} \)
An indium trichloride-mediated cross-cyclisation reaction of 3-trimethylsilylallyltributylstannane 67 with 2 equivalents of an aldehyde led to the formation of 2,6-dialkyl-3,4-dihydropyrans 68 with cis diastereoselectivity (Scheme 48).\textsuperscript{114} With this methodology it is only possible to introduce the same substituents in the positions 2 and 6 of the dihydropyran core.

Optically active dihydropyrans 70 and 72 have been formed by a direct coupling-cyclization of the chiral silanes 69 and 71 with a wide range of aldehydes in the presence of catalytic amounts of trimethylsilyl trifluoromethanesulfonate (Scheme 49).\textsuperscript{115}
Despite these ring forming reactions, novel methods are still required for the preparation of natural products and the synthesis of their analogues.

3.5 Fluorinated heterocycles

In recent years the introduction of the difluoro-fragment into organic compounds has become an attractive sphere of research. Such molecules can inhibit one or more enzymes or can be partially metabolised into more bioactive substances. Halodifluoroacetates, chlorodifluoromethyl ketones and bromodifluoromethyl acetylene have been used widely as reagents to introduce a CF$_2$ moiety into molecules.

As fluorine chemistry became more popular, it was inevitable that chemists would turn their attention to the preparation of fluorinated carbohydrates. Such targets attracted scientists by their important role in enzyme-carbohydrate interactions and also by their potential biological activity. Fluorinated carbohydrates maintain much of the reactivity of the natural saccharides, but at the same time prevent hydrogen bonding interactions with nucleic acids or proteins.

Analogues of difluorinated carbohydrates are usually prepared by DAST difluorination of molecules with ketonic carbonyl groups. Percy’s approach was based on metallated difluoroenol derivatives by using a ring closing metathesis (RCM) method. He employed allylindium chemistry and at the first stage was synthesised homoallyl alcohol 73 in good yields.

![Scheme 50]

This is followed by $O$-allylation employing allyl bromide 74 and sodium hydroxide in the presence of Bu$_4$NHSO$_4$:
The final stage used RCM to furnish the difluorinated heterocycle 76 (Scheme 52).\(^{121,122}\)

Several other groups have used DAST to introduce fluorine in sugars, including Liu, who has reported 10 step route to TDP 4,4-difluoro-2,4,6-trideoxy-sugar, 77.\(^{124}\)

The two fluorine atoms stabilise the bond to the TDP leaving group. Such compounds have the potential to probe the binding sites of glycosyltransferase enzymes.\(^{125}\)

Taguchi’s group\(^{126}\) prepared dihydropyrene 79 using a hetero Diels-Alder reaction employing 1,1-difluoro-2,4-dialkoxy-1,3-butadiene 78. The product 79 was developed to a 2,4-dideoxy-4,4-difluorosugar 80, but the final stage, obtaining 4-deoxy-4,4-difluorosugar 81 was not reported (Scheme 53)
There have been some other attempts to synthesise difluoroheterocycles. Hu utilized a Reformatsky reaction to obtain 4,4-difluoro-3-ethoxy-2-lactanone 83 using ethyl 4,4-difluoro-ethoxy-4-halocrotonate 82, an aldehyde and Zn powder (Scheme 54):

\[
\text{OEt} \quad \text{BrCF}_2 \quad \text{CO}_2\text{Et} + \underbrace{\begin{array}{c}
\text{OEt} \\
\text{BrCF}_2 \\
\text{R} \\
\text{H}
\end{array}}_{82} \rightarrow \underbrace{\begin{array}{c}
\text{OEt} \\
\text{F} \\
\text{R} \\
\text{O}
\end{array}}_{83}
\]

Scheme 54

Recently an attractive method to obtain monofluorinated carbohydrates has been introduced. \(N,N\)-Diethyl- \(\alpha,\alpha\)-difluoro-(\(m\)-methylbenzyl)amine 84 has been found to be a selective reagent for synthesising fluorinated carbohydrates. Hara has employed this reagent for deoxyfluorination of primary hydroxyl groups and anomeric hydroxyl groups in sugars as well.

\[
\text{O} \quad \text{O} \\
\text{O} \quad \text{O} \\
\text{O} \quad \text{O} \\
\text{OH} \\
\text{F} \\
\text{NEt}_2
\quad \underbrace{\begin{array}{c}
\text{O} \\
\text{O} \\
\text{O} \\
\text{O} \\
\text{F}
\end{array}}_{84} \rightarrow \underbrace{\begin{array}{c}
\text{F} \\
\text{O} \\
\text{O} \\
\text{O} \\
\text{O}
\end{array}}_{84_1}
\]

Scheme 55

At the early stages conventional conditions were exploited, but later the yield was significantly increased by microwave irradiation.

3.6 Aims

Fluorosugars show great potential for the creation of probes and inhibitors of sugar processing enzymes. This is a new direction of research and there are no reports available about them.

Given the demand for these compounds, it was planned to continue interests in fluorine-containing compounds by devising a novel method for the synthesis of fluorine containing heterocycles. Current expertise in the research group on the Prins reaction would form the
basis for this work, with the fluorine to be incorporated into one of the reactants and also via a Lewis acid mediated cyclisation.

3.7. The Prins Reaction

The Prins reaction is generally considered as the addition of aldehydes and ketones to alkenes in the presence of Brønsted acids.\textsuperscript{129-131} Under Lewis acid conditions a range of carbonyl compounds react with alkenes to offer homoallylic alcohol ene adducts, but in some cases γ-chloro alcohols are also formed as by products.\textsuperscript{132,133} During the first stage, a carbonyl compound and alkene react to generate a β-hydroxy carbocation which then reacts either with a nucleophile (chloride, water) to give 85 or a second molecule of aldehyde to give 86. When loosing a proton it transforms into a homoallylic alcohol 87.\textsuperscript{134}

\begin{align*}
\text{O} & \quad + \quad \text{CH}_2=\text{CH}_2 \quad \xrightarrow{HX} \quad \text{OH}^+ \quad \xrightarrow{\text{X}} \quad \text{OH}^+ \\
& \quad \text{R}_1X \quad \text{R}_2 \quad \text{R}_1X \quad \text{R}_2 \\
& \quad \text{R}^1\text{CHO} \quad \text{H}_2 \quad \text{R}^1\text{CHO} \quad \text{OH} \quad \text{OH} \quad \text{OH} \\
& \quad \text{R}_1 \quad \text{R}_2 \quad \text{R}_1 \quad \text{R}_2 \quad \text{R}_1 \quad \text{R}_2 \\
& \quad \text{Scheme 56}
\end{align*}

Intramolecular Prins and ene reactions are divided into three types, depending on the connectivity pattern of the carbonyl group and alkene.\textsuperscript{135}

Type I ene reactions are restricted to the formation of five and six membered rings. The carbonyl group creates a bond to the internal carbon of the double bond. In the Prins reaction, the reaction ends with products derived from 88, but with the ene reaction 89 is obtained (Scheme 57).\textsuperscript{134}
Chapter 3: Introduction to Heterocycles

Levan Pivnevi

Although Type II can form five-membered rings, in practice it is restricted to the formation of six- and seven-membered rings. Here, the carbonyl group creates a bond to the terminal carbon of the double bond. The Prins adducts come out from the products derived from 90, and the ene reaction gives 91, (Scheme 58)

Type III reactions use an acetal, hemiacetal or enol ethers, which is converted to a cation 92. This cyclises to 93 or 94 depending on the substitution pattern of the double bond (Scheme 59)
If the internal end of the double bond is highly substituted, cyclisation proceeds in an endocyclic mode to give 94. This reaction has been widely reported for the formation of 4-chlorotetrahydropyrans 95. (Scheme 60)\cite{129-131,136-140}

![Scheme 60]

Interaction of alkoxy silanes 96 with aldehydes and AlCl₃, SnCl₄ or TiCl₄ gives cis-2,6-dialkyl-4-chlorotetrahydropyrans 97\cite{134,140} (Scheme 61)

![Scheme 61]

The same, type III cyclisations have been used by Overman\cite{141,142} to obtain eight and nine-membered cyclic ethers. He treated 98 with 2 equiv. of SnCl₄ for 13h at -20 °C and obtained 96 that cyclises to give a 2:1 mixture of 100 and 101\cite{143} (Scheme 62).\cite{134}

![Scheme 62]

The pyran skeleton forms the basis of many natural products and a large number of methodologies have been published for the synthesis of these oxygen-containing heterocycles.\cite{114,144-148}
Chapter 4

RESULTS & DISCUSSION II: NOVEL METHODS TO PREPARE FLUORINATED HETEROCYCLES
Chapter 4: Results and Discussion II: Heterocycles

4.1 Introduction

Based on previous results within our group of studies on the Prins and silyl-Prins reactions,\textsuperscript{149,150} indium trichloride was known to be a mild Lewis acid that is: easy to handle, a solid, non-toxic, and not very hygroscopic. Most importantly of all, it gave good reaction yields. This project aimed to use Prins-type cyclisation reactions employing indium-based Lewis acids to obtain a range of oxygen containing heterocycles, including fluorinated derivatives.

4.2 Synthesis of Dihydropyran from Acetylenes

We have previously reported the synthesis of dihydropyran from silylated homoallylic alcohols. In place of this starting material, which takes two steps to prepare, attention focussed on using alkynes as suitable precursors to dihydropyran.

\textbf{Previous Work:}

\textbf{Aim:}

![Scheme 63](image)

In a preliminary test reaction, phenylacetaldehyde 103 (1 eq) was added to a solution of 3-butyn-1-ol 102 (1 eq) in dichloromethane at room temperature followed by indium chloride (1 eq). These were the identical conditions developed for the silyl-Prins reactions. Pleasingly, the cyclised 4-chlorodihydropyran derivative 104 was obtained in 40% yield.

![Scheme 64](image)

A wide range of aldehydes and alkynes were then employed in this reaction; the results are summarised in Table 8.
Table 8: Cyclisation of homoacetylenic alcohols with aldehydes and indium trichloride.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Alkyne</th>
<th>Aldehyde</th>
<th>Lewis Acid</th>
<th>Solvent</th>
<th>% Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R = H</td>
<td></td>
<td>InCl₃</td>
<td>DCM</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>R = H</td>
<td></td>
<td>InCl₃</td>
<td>DCM</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>R = H</td>
<td></td>
<td>InCl₃</td>
<td>DCM</td>
<td>63</td>
</tr>
<tr>
<td>4</td>
<td>R = H</td>
<td></td>
<td>InCl₃</td>
<td>DCM</td>
<td>48</td>
</tr>
<tr>
<td>5</td>
<td>R = H</td>
<td></td>
<td>InCl₃</td>
<td>DCM</td>
<td>56</td>
</tr>
<tr>
<td>6</td>
<td>R = H</td>
<td></td>
<td>InCl₃</td>
<td>DCM</td>
<td>48</td>
</tr>
<tr>
<td>7</td>
<td>R = H</td>
<td></td>
<td>InCl₃</td>
<td>DCM</td>
<td>41</td>
</tr>
<tr>
<td>8</td>
<td>R = H</td>
<td></td>
<td>InCl₃</td>
<td>DCM</td>
<td>41</td>
</tr>
<tr>
<td>9</td>
<td>R = H</td>
<td></td>
<td>InBr₃</td>
<td>DCM</td>
<td>76(mixture)</td>
</tr>
<tr>
<td>10</td>
<td>R = H</td>
<td></td>
<td>InBr₃</td>
<td>DCM</td>
<td>53(mixture)</td>
</tr>
<tr>
<td>11</td>
<td>R = H</td>
<td></td>
<td>InBr₃</td>
<td>DCM</td>
<td>51(mixture)</td>
</tr>
<tr>
<td>12</td>
<td>R = H</td>
<td></td>
<td>InCl₃</td>
<td>DCM</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>R = H</td>
<td></td>
<td>InCl₃</td>
<td>DCM</td>
<td>-</td>
</tr>
<tr>
<td>14</td>
<td>R = H</td>
<td></td>
<td>InCl₃</td>
<td>DCM</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>R¹ = Me</td>
<td></td>
<td>InCl₃</td>
<td>DCM</td>
<td>-</td>
</tr>
<tr>
<td>16</td>
<td>R¹ = Me</td>
<td></td>
<td>InCl₃</td>
<td>DCM</td>
<td>-</td>
</tr>
<tr>
<td>17</td>
<td>R¹ = Me</td>
<td></td>
<td>InCl₃</td>
<td>DCM</td>
<td>-</td>
</tr>
<tr>
<td>18</td>
<td>R = H</td>
<td></td>
<td>BF₃O(C₂H₅)₂</td>
<td>DCM</td>
<td>22</td>
</tr>
<tr>
<td>19</td>
<td>R = H</td>
<td></td>
<td>TMSOSO₂CF₃</td>
<td>DCM</td>
<td>52</td>
</tr>
</tbody>
</table>
Simple aldehydes were found to react well with 3-butyln-1-ol at room temperature in short reaction times (5 min) in good to excellent yields and as a single diastereomer (Table 8, entries 1-8). As with related cyclisations using indium trichloride, aromatic aldehydes were found to be much less reactive compared to aliphatic ones (entries 7, 12 & 14); only 4-nitrobenzaldehyde gave a product, and this reaction required longer reaction times and heating to reflux for two h. α,β-Unsaturated compounds also failed to give any product either at ambient temperature or reflux (entry 13).

Of more interest was the observation that pent-4-yn-2-ol gave no equivalent product with any aldehyde, only starting material being recovered (entries 15-17). There is no obvious explanation for this observation, but it is in keeping with those reported by Martin in a related study using aluminium-based Lewis acids.

Using other Lewis acids gave interesting results. Replacing indium trichloride with indium tribromide gave the vinyl bromide as the major product (entries 9 & 10), although a second, inseparable product was identified from these reactions as the chlorinated product. Although inseparable by chromatography, by GCMS, the ratio of the two products bromide 110:chloride 109 was 2.5:1 (Scheme 66).
The use of indium tribromide was also investigated using phenylacetaldehyde. As in the previous example, the experiment afforded an inseparable mixture of bromo 111 and chloro 104 substituted molecules in the ratio (according to GCMS) 2.5:1 (Scheme 67).

Indium tribromide was employed in the reaction with hexanal 112 (entry 11). As in the previous examples with InBr₃ the reaction completed with inseparable mixture of chloro 113 and bromo 114 compounds in the ratio (according to GCMS) 3:1 (Scheme 68).

The indium tribromide was pure by mass spectrometry and microanalysis, and thus not the source of chlorine. Therefore the only explanation is that the chlorine must come via the solvent, dichloromethane. Therefore, using this method to prepare heterocyclic vinylbromides would appear to be inefficient. Obviously, to overcome this we must remove the possibility of halogen exchange, and this can be done through the use of dibromomethane (entry 20). In this way, the brominated product comparable to those from the InCl₃/DCM combination were obtained (Scheme 69).
In addition, other solvents were tested: tetrahydrofuran and acetonitrile. Two identical experiments were set in parallel to each other with reactants that were known to react well together: 3-butyne-1-ol 102, hexanal 112, and indium trichloride as the Lewis acid. A second set of reactions was performed using indium tribromide in place of indium trichloride. None of the reactions in these solvents gave any product, or indeed any identifiable material (Scheme 70).

Employing boron trifluoride (entry 18) failed to give any product, either at room temperature of -78 °C. Using TMSOTf, however, was a useful alternative to indium trichloride, generating a vinyl triflate in the product. The reaction, however, required much lower temperatures, -78 °C, to proceed (the reaction mixture decomposed if the reaction was performed at room temperature).

Single experiment has been performed using 3-buten-1-ol 113 and phenylacetaldehyde 103 in chloroform. Overnight reaction gave the product in a good yield (Scheme 71)
As an intellectual curiosity, and linking back to chapters 1 and 2, it was decided to see if dihydropyrans bearing a fluorous chain could be prepared *i.e.* to introduce a fluorous chain *via* a fluorous aldehyde. The targeted fluorine-containing aldehydes were identified as being potentially available from commercial alcohols under Swern oxidation conditions. 1H,1H,2H,2H-Tridecafluoro octanol 34 and 4,4,4-trifluorobutanol 115 were selected (Scheme 72).

Unfortunately, both reactions failed and these aldehydes could not be tested.

The results have shown that, beside a few negative examples, indium chloride is a reliable Lewis acid except for a few Prins-cyclisation reactions of acetylenes.

### 4.3 Application of Prins-type reactions to the synthesis of fluorinated dihydropyrans

The Prins cyclisation is also known as an efficient method for the preparation of tetrahydropyrans.149 Previous work in our group and also by Li152 has shown that 4-halotetrahydropyrans are available by the reaction of homoallylic alcohols with aldehydes and a Lewis acid (Scheme 73).
It was proposed that it may be possible to prepare fluorinated tetrahydropyrans, as precursors to fluorinated heterocycles and sugars, by incorporating fluorine into the homoallylic alcohol starting material.

There are number of examples of opening epoxide rings by fluoride to obtain fluorine containing products.\(^{152-160}\) The Baklouti group also demonstrated\(^{161}\) the possibility of epoxide ring opening at room temperature by using hydrogen fluoride and pyridine. Another work of Baklouti’s group, in which triethylamine trihydrofluoride 116 as a nucleophile for epoxide opening to obtain mono-fluorinated alcohols as the final product\(^{162}\) was of particular interest to us in our desire to prepare fluorine-containing cyclisation precursors.

Under a nitrogen atmosphere butadiene monoxide 117 (1 eq) was treated with triethylamine trihydrofluoride 118 (2 eq) for 24 h at room temperature. After work-up, a crude mixture containing the product, 2-fluorobut-3-en-1-ol 118 was obtained (Scheme 74).\(^{162}\)

Initial attempts at performing cyclisation reactions using this compound did not furnish the desired product. This is believed to be due to incomplete formation of 118. Thus the conditions for epoxide opening reaction were changed and instead of stirring for 24 h at...
room temperature, the mixture was heated at reflux for 70°C for 8h. The title compound 118 was purified by distillation as a colourless oil in good yield (62%).

The purified product was then used in a Prins cyclisation reaction.\textsuperscript{162} It was reacted with phenylacetaldehyde 103 and indium chloride with a ratio of 1:1:1 to obtain a dihalogenated tetrahydropyran, with chlorine at the 4-position and fluorine at the 5-position (119) but initially only in trace amounts.

Two further reactions employing 118 with either hexanal or phenylacetaldehyde with indium chloride in 1:1:1 molar ratio at room temperature, even at prolonged reaction times, failed to produce significant yields of product.

It was decided to vary the ratio between reactants and also instead of stirring at room temperature to heat the reaction mixture to reflux. These variations worked very well, with the best yields of product being obtained with a ratio of alcohol:aldehyde:indium trichloride 1:1.5:2 and heating to reflux for as long as TLC indicated that there was still starting material present. This became the general method for the preparation of fluorinated tetrahydropyrans. The results for various aldehydes are presented in Table 9.
Table 9: Reaction of various aldehydes with 2-fluorobut-3-en-1-ol 118.

![Chemical structure diagram]

<table>
<thead>
<tr>
<th>Entry</th>
<th>Aldehyde</th>
<th>Lewis Acid</th>
<th>Solvent</th>
<th>% Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image" alt="Ph aldehyde" /></td>
<td>InCl₃</td>
<td>DCM</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td><img src="image" alt="Ph aldehyde" /></td>
<td>InCl₃</td>
<td>DCM</td>
<td>65</td>
</tr>
<tr>
<td>3</td>
<td><img src="image" alt="Ph aldehyde" /></td>
<td>InCl₃</td>
<td>DCM</td>
<td>Trace amounts</td>
</tr>
<tr>
<td>4</td>
<td><img src="image" alt="Ph aldehyde" /></td>
<td>InCl₃</td>
<td>DCM</td>
<td>61</td>
</tr>
<tr>
<td>5</td>
<td><img src="image" alt="Ph aldehyde" /></td>
<td>InCl₃</td>
<td>DCM</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td><img src="image" alt="Ph aldehyde" /></td>
<td>TMSOSO₂CF₃</td>
<td>DCM</td>
<td>56*</td>
</tr>
<tr>
<td>7</td>
<td><img src="image" alt="Ph aldehyde" /></td>
<td>BF₃OEt₂</td>
<td>DCM</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td><img src="image" alt="Ph aldehyde" /></td>
<td>BF₃OEt₂</td>
<td>DCM</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td><img src="image" alt="Ph aldehyde" /></td>
<td>AlCl₃</td>
<td>DCM</td>
<td>-</td>
</tr>
</tbody>
</table>

* not of the tetrahydropyran but rather the fluorinated dihydropyran.

As with previous Prins cyclisations, good yields were obtained under the optimised reaction conditions and molar ratios for a range of aliphatic aldehyde (entries 1-4). The products were always obtained as single diastereomers. Once again, aromatic compounds are much less successful in these reactions and even 4-nitrobenzaldehyde, previously the most reactive of the benzaldehydes, failed to give any identifiable product.

Most pleasing was the fact that the presence of the highly electronegative fluorine atom appeared to have very little effect on the Prins cyclisation, and in particular on the stability of the cation 120. The stability of this cation was considered as crucial to the cyclisation, but pleasingly the electron withdrawing effect of the fluorine atom does not appear to have
affected this process, with yields for this cyclisation only being slightly lower than those obtained in non-fluorine containing Prins cyclisations.

Finally, it was necessary to examine the stereochemistry of the newly formed heterocycles. nOe NMR experiments were performed on all the fluorinated heterocycles prepared (entries 1-5) and all were found to have the same stereochemistry: the substituents were orientated in an all-\(\text{cis}\) conformation. At present, there is no other data (crystallography) to support the nOe assignments, although the results of the nOe experiments were almost identical for each of the fluorinated compounds prepared.

The final part of this section of the project involved looking at other Lewis acids, in order to introduce different substituents at the 4-position, in place of chlorine. Reactions were set-up using 2-flurobut-3-en-1-ol 118 and phenylacetaldehyde 103 and either trimethylsilyl triflate, boron trifluoride etherate or aluminium chloride (Scheme 77). All three failed to give the desired tetrahydropyrans.
However, a dihydropyran product was obtained from the reaction with TMSOTf (Table 9 entry 7). Rather than the 4-OTf substituted product, the dihydropyran was isolated in 56% yield. It is believed that the tetrahydropyran was probably first formed, but then elimination of the triflate group gave the obtained product. The substituents at the 2- and 5-positions maintained a cis-relationship, as judged by nOe studies.

4.4 The silyl-Prins Reaction and fluorinated heterocycles

Our research group has also developed a method for the preparation of dihydropyrans known as the silyl-Prins reaction.\textsuperscript{149} This reaction involves the reaction of a vinylsilane-containing homoallylic alcohol with an aldehyde and Lewis acid, to give excellent yields of dihydropyrans.

We set out to produce fluorinated dihydropyrans via this methodology, using fluorinated vinylsilane precursors. This method has the additional advantage that the carbocation intermediate 120 has additional stabilisation via the $\beta$-effect from the neighbouring silicon atom, prior to being eliminated to form the endocyclic double bond. First, it was necessary to prepare the fluorine containing vinylsilane 121, and it was proposed to do this via a metathesis reaction.
4.5 Methathesis

The process, where unsaturated carbon-carbon bonds are rearranged in the presence of metal carbene complexes is called olefin metathesis.\textsuperscript{163-165} In the early stages of development, olefin metathesis was carried out using ill-defined multicomponent catalyst systems.\textsuperscript{166-168} Only in the past few years have well-defined single component metal carbene complexes been prepared and used in olefin metathesis.\textsuperscript{169} Both functional groups in the substrate and solvents (including oxygen and water) can interfere with the metathesis catalysts. After a broad range of research, Grubbs has found that ruthenium reacts preferentially with carbon-carbon double bonds, making ruthenium-containing catalysts very stable to alcohols, amides, aldehydes and carboxylic acids.\textsuperscript{169}

The reactions can be grouped into the three types of methathesis:\textsuperscript{122}

1. Ring-Opening Metathesis Polymerisation (ROMP)

\[ \text{Scheme 80} \]

2. Ring-Closing Methathesis (RCM)

\[ \text{Scheme 81} \]

3. Acyclic Cross Metathesis (ADMET)

\[ \text{Scheme 82} \]

The first two types (Scheme 80 and 81) are widely used. Much less effort has been concentrated on acyclic cross-methathesis (Scheme 82).\textsuperscript{170,171} Until recently, selective cross-methathesis was used for styrenes, acrylonitrile and allylsilanes\textsuperscript{172}. The $\beta$-effect of silicon means allyltrimethylsilane is a useful reagent for cross-methathesis\textsuperscript{170} and vinylsilanes have also been employed. In this article the authors demonstrated the success
of cross-metathesis reactions using epoxyalkenes. Based on this approach, this project aimed to utilise the cross-metathesis method using vinyltrimethylsilane and 2-fluorobut-3-en-1-ol 118 to prepare 121 and then to use this in silyl-Prins cyclisation reactions.

First, the cross-metathesis reaction was tested on non-fluorinated compounds. Vinyltrimethylsilane 122 and 2-propen-1-ol 123 in dry dichloromethane was mixed and a solution of Grubb’s catalyst (type I) in dry dichloromethane was added. After 16 h of stirring at room temperature the desired 3-trimethylsilylprop-2-en-1-ol 124 was not obtained (Scheme 83) only starting material being recovered.

This experiment was repeated several times, but with unsuccessful results. Changing to Grubb’s type II catalyst also failed to give any of the desired product. Time prevented any alternative methods for the preparation of 121 being attempted.

4.6 Conclusions

It has been shown that both acetylenes and fluorinated homoallylic alcohols may be used in the Prins cyclisation reaction, to give single diastereomeric products in good yields. This is the first time that fluorinated compounds have been employed in this reaction and the first time that fluorinated tetrahydropyrans have been prepared in this manner. This reaction, in particular, warrants further investigation, for example using additional substituents in the starting material as well as further elaboration of the tetrahydropyran products. Obviously, these compounds will also be of potential interest to biologists.
Chapter 5

RESULTS & DISCUSSION III: NATURAL PRODUCT SYNTHESSES USING THE PRINS CYCLISATION
A perfume is a fragrant product that results from the artful blending of certain odoriferous substances in appropriate proportions. Raw materials used in perfumery include natural products of plant or animal origin and synthetic materials. Certain animal secretions contain odoriferous substances that increase the lasting qualities of perfumes. Such substances and some of their constituents act as fixatives, preventing more volatile perfume ingredients from evaporating too rapidly. Examples of animal product fixatives and fragrances include ambergris from the sperm whale, castor from beaver, civet from the civet cat and musk from the musk deer.

As the final part of the project, the Prins cyclisation methodology developed both in this project and within our research group will be applied to the synthesis of two natural, fragrant compounds.

5.1. Synthesis of (±)-(S,S)-(cis-6-methyltetrahydropyran-2-yl)acetic acid and its previous syntheses

The African civet cat (*Viverra civetta*, Fig. 11) belongs to a large group of mostly nocturnal mammals of the Old World family *Viverridae* (civet family). Civets are not true cats, but the civet family is related to the cat family (*Felidae*) and most civets have catlike bodies, long tails, and weasel-like faces.
This group has, for a long time, been employed in the perfume trade, because of their scent-producing glands, located in a double pouch near the genitals. The fatty yellow secretion of this gland has a distinctive musky odour used for territorial marking. Commercially, this substance is known as civet and is used as a perfume fixative. The World Society for the Protection of Animals has reported how African civets have been taken from the wild and made to spend their lives kept individually in primitive and small wooden cages. Typically, the civet is pinned down and its rear end pulled out so that the perineal gland at the base of its tail is exposed. The gland is then opened up, squeezed and the resulting musk scraped out. This can take several minutes and involves injuries to the civet. Today, the African civets are classified as an endangered species.

One of the most important components isolated from civet is (+)-(S,S)-(cis-6-methyltetrahydropyran-2-yl)acetic acid, 125, the structure of which was identified and confirmed for the first time by Maurer and co-workers in 1979. In the past twenty years a number of different approaches to (+)-(S,S)-(cis-6-methyltetrahydropyran-2-yl)acetic acid in its racemic form have been published. In this short overview methods used for the preparation of civet using ring formation as the key synthetic step, will be presented.

5.1.1. Ring formation via cycloaddition reactions

One of the first methods used to confirm the structure and to assign the relative configuration of (cis-6-methyltetrahydropyran-2-yl)acetic acid (119) was based on Diels-Alder chemistry (Scheme 84).

\[
\begin{array}{c}
\text{acrylonitrile} \rightarrow \text{cis-119} \quad \text{trans-119}
\end{array}
\]

Scheme 84

Mundy and Kim have reported a simple stereospecific synthesis of racemic (cis-6-methyltetrahydropyran-2-yl)acetic acid based on dimerization of methyl vinyl ketone (Scheme 85).
5.1.2. Ring formation via 6-exo-cyclisation reactions

(+)-(S,S)-(Cis-6-methyltetrahydropyran-2-yl)acetic acid was synthesised using, as the key step, a 6-exo cyclisation reaction of the triol 126 in the presence of trimethyl ortho-benzoate and trifluoromethansulfonic acid as the key step (Scheme 86). \(^{176}\)

The palladium catalysed cyclisation of the chiral alcohol 127 at room temperature gave 128 in a 94% yield, without need to further activate the nucleophilic hydroxyl group (Scheme 87). \(^{177}\)

Yamamoto has published the synthesis of the civet cat constituent by the reductive cleavage of bicyclic acetals (Scheme 86). \(^{178}\) Slow addition of titanium tetrachloride into a solution of bicyclic acetal 131 and diphenylsilane at \(-78\) °C for 4 hours afforded the cis isomer 132 as major product (82% yield). The stereochemistry of was determined by oxidation (CrO₃) to the known carboxylic acid.
Chapter 5: Natural Product Syntheses

Levan Pivnevi

![Chemical structure](image)

**Scheme 88**

A similar route, using reductive cleavage of bicyclic ketals, was used by Kotsuki\(^{179}\) (Scheme 89). The combination of zinc borohydride and titanium tetrachloride acts as a mild reducing agent for the reductive cleavage of bicyclic ketals.

![Chemical structure](image)

**Scheme 89**

Ley synthesised \(\text{(+)}\)-(S,S)-(cis-6-methyltetrahydropyran-2-yl)acetic acid from commercially available \((-\text{)}\)-(S)-propylene oxide (Scheme 90).\(^{180}\) Ring-opening of \((-\text{)}\)-(S)-propylene oxide (133) with butenyl Grignard gave alkenol 134 in 95% yield. Conversion of 134 to the lactol 135 (89% yield) via open-chain aldehyde was performed by ozonolysis at \(-78\ °\text{C}\).
One of the most direct and specific approaches to the racemic form of the Civet constituent uses a radical cyclisation reaction and is depicted in Scheme 91.\textsuperscript{181} Under high dilution radical cyclisation conditions using tributylstannane, six-membered cyclic ether \textit{137} formation was achieved in high yields and diastereoselectivity.

Gallagher\textsuperscript{182} has published a stereoselective route to \textit{cis}-2,6-disubstituted tetrahydropyrans using silver-mediated cyclisation of secondary allenic alcohols \textit{139} (Scheme 92).

Mandai has developed a new synthetic method for the preparation of \textit{cis}-2,6-disubstituted tetrahydropyrans by an intramolecular 1,4-addition of \(\alpha,\beta\)-unsaturated sulfoxides and has applied it to the enantioselective synthesis of (+)- and (-)-(\textit{cis}-6-methyltetrahydropyran-2-yl)acetic acids (Scheme 93).\textsuperscript{183}
An intramolecular Michael addition of the type shown in Scheme 94 has also been used as a key cyclisation step to prepare (+)-(S,S)-(cis-6-methyltetrahydropyran-2-yl)acetic acid.\textsuperscript{184}

Seebach and Pohmakotr\textsuperscript{185} observed that the treatment of $E$-hydroxyketone 140 with sodium methoxide causes the cyclisation to a (3:2)-mixture of cis- and trans-products 141. The formation of trans-141 as a kinetic product was observed after 1-2 hours at room temperature, while the thermodynamic cis-141 product was quantitatively isolated after 3-4 days (Scheme 95).\textsuperscript{185}
5.1.4. Ring formation via condensation reactions

(±)-(cis-6-Methyltetrahydropyran-2-yl)acetic acid was synthesised by the condensation reaction of acetaldehyde and the unsaturated alcohol 142 in the presence of aluminium tribromide (Scheme 96).\(^\text{186}\)

![Scheme 96](image)

The tetrahydropyran 143 was prepared in a one-pot synthesis from the optically active alkoxyallylsilane 144, using acetaldehyde and 3-(benzyloxy)propanal as the aldehyde components and aluminium trichloride as the Lewis acid (Scheme 97).\(^\text{187}\)

![Scheme 97](image)

Nussbaumer and Fráter have published the synthesis of (±)-(cis-6-methyltetrahydropyran-2-yl)acetic acid from (±)-4-penten-2-ol (Scheme 98).\(^\text{188}\) Addition of (±)-4-penten-2-ol to methyl propiolate in the presence of N-methylmorpholine afforded the β-alkenyloxyacrylate 145, which upon exposure to trifluoroacetic acid in DCM at 0 °C cyclized to a mixture of labile trifluoroacetates.
5.1.5. Non-cyclisation based methods for the preparation of the Civet cat component

Scheme 99 outlines the employment of a deoxygenated sugar molecule 146 as a chiral building block in the total synthesis of \((+)-(S,S)-(\text{cis-6-methyltetrahydropyran-2-yl})\text{acetic acid.}^{189}

Several methods for the synthesis of the optically pure form of the Civet cat constituent are based on the chiral catalytic properties of enzymes. \((-)-(S)-5\text{-Hexanolide 147} is readily available as a colourless oil in an excellent enantiomeric excess by an enzymatic resolution of its racemate (Scheme 100),\textsuperscript{190} by horse liver esterase (HLE). \((-)-(S)-5\text{-Hexanolide was reduced by lithium aluminium hydride in diethyl ether to the corresponding lactol, which was then converted to the natural product 119 in an excellent chemical yield (66%).}^{190}
Another enzymatically based approach to the optically active Civet component is outlined in Scheme 101.\textsuperscript{191} Commercially available porcine pancreatic lipase (PPL) is one of the most widely applied enzymes in stereospecific transformations on symmetrical substrates. The key stereochemistry of the starting chiron for the synthesis was set by stereoselective PPL-catalysed hydrolysis of 149 to give the alcohol-ester 150 in 55% e.e. and 77% isolated yield. Oxidation of 150 to 151 proceeded smoothly in a 94% yield. Homologation of 151 was effected in a 42% yield by the Arndt-Eistert procedure, a reaction that is known to proceed with retention of configuration at the α-position of the carboxyl function. The overall yield of the Civet cat constituent was 18%, with the target product having the same e.e. (55%) as the starting chiron.

![Scheme 101](image)
5.2. Synthesis of (±)-(cis-6-methyltetrahydropyran-2-yl)acetic acid using the silyl-Prins cyclisation reaction

The retrosynthetic approach to the Civet cat constituent, (±)-(cis-6-methyltetrahydropyran-2-yl)acetic acid utilising our silyl-Prins methodology is presented in Scheme 100. This methodology has been previously described in chapter 4 and involves the reaction of an silylated homoallylic alcohol with an aldehyde in the presence of a Lewis acid, such as indium trichloride to give a dihydropyran in good yield and excellent diastereoselectivity, producing a single diastereomer with a cis-geometry across the oxygen atom of the ring.

It was envisaged that the tetrahydropyran core of the natural product could be obtained by reduction of the appropriate cis-disubstituted dihydropyran derivative 153. The stereochemistry for the final product would be set up during a cyclisation process, such as the silyl-Prins reaction. Two disconnections, between C(2)-C(3) and C(2)-O, to identify
optically pure \((R)-(\rightarrow)-Z-5\text{-trimethylsilylpent-4-en-2-ol (156)}\) as a precursor. In turn 156 could be easily obtained in a two step process from \((S)-(\rightarrow)\text{-propylene-oxide. The aldehyde component 155 containing a protected alcohol function could be easily prepared in two steps from commercially available propane-1,3-diol (154).}

The aim of this investigation was to develop a synthetic route towards optically active \((S,S)-(\rightarrow)-(\text{cis-6-methyltetrahydropyran-2-yl})\text{acetic acid using the silyl-Prins reaction.}

The synthesis of racemic \((\pm)-(\text{cis-6-methyltetrahydropyran-2-yl})\text{acetic acid was first carried out. Monoprotection of propane-1,3-diol (154) afforded 3-benzyloxy-1-propanol (159) in a 44\% yield that was further oxidised under Swern conditions to give 3-benzyloxypropionaldehyde (158) in 77\% yield (Scheme 104).}

\[
\begin{align*}
\text{HO} & \text{OH} \\
\text{154} & \text{DMSO, THF} & \text{Ph} & \text{DMSO, COCl} & \text{CH}_2\text{Cl}_2, \text{NEt}_3 \\
& & & -78° \text{C} & -78° \text{C to r.t.} \\
& & & & (77\%) \\
\text{158} (44\%) & \text{BnBr, KOH} & \text{HO} & \text{O} & \text{O} \text{N} \\
& & \text{DMSO-THF} & \text{Ph} & \text{CH}_2\text{Cl}_2, \text{NEt}_3 \\
\end{align*}
\]

Scheme 103

Racemic \((\pm)-Z-5\text{-trimethylsilylpent-4-en-2-ol (156)}\) was prepared in a two step process: first the trimethylsilyl protection of the acetylene of pent-4-yn-2-ol followed by DiBAL reduction, to give the product in 89\% overall yield.

\[
\begin{align*}
\text{1. 2 eq. nBuLi, THF, -78°C} \\
\text{2. 2 eq. TMSI, -78°C to r.t.} \\
\text{3. dil. HCl} \\
\text{4. 3 eq. DiBAL, 0°C to reflux} \\
\end{align*}
\]

Scheme 104

The silyl-Prins reaction using 158 with \((\pm)-Z-5\text{-trimethylsilylpent-4-en-2-ol (156)}\) under standard conditions afforded \((\pm)-(\text{cis-2-(2-benzyloxyethyl)-6-methyl-5,6-dihydro-2H-pyran (153)}\) in a 95\% yield (Scheme 103).
Chapter 5: Natural Product Syntheses

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Scheme 105

The relative stereochemistry of the cyclisation product 153 was determined by nOe studies.

<table>
<thead>
<tr>
<th>Irradiated</th>
<th>Enhanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>C(3)H</td>
<td>C(2)H, +3.0%</td>
</tr>
<tr>
<td></td>
<td>C(4)H, +6.6%</td>
</tr>
<tr>
<td></td>
<td>OCH$_2$CH$_2$, +2.6%</td>
</tr>
<tr>
<td>C(4)H</td>
<td>C(3)H, +4.1%</td>
</tr>
<tr>
<td></td>
<td>C(5)H, +6.2%</td>
</tr>
<tr>
<td>C(6)CH$_3$</td>
<td>[C(6)H+PhCH$_2$OCH$_2$], +3.3%</td>
</tr>
<tr>
<td></td>
<td>C(5)H$_2$, +1.9%</td>
</tr>
<tr>
<td>C(2)H</td>
<td>[C(6)H+PhCH$_2$OCH$_2$], +9.2%</td>
</tr>
<tr>
<td></td>
<td>OCH$_2$CH$_2$, +3.8%</td>
</tr>
<tr>
<td></td>
<td>C(3)H, +3.1%</td>
</tr>
</tbody>
</table>

Simultaneous removal of the benzyl protection and the reduction of the endocyclic double bond was achieved by hydrogenation on palladium in dry ethanol over 19 hours (Scheme 105).
Subsequent Jones’ oxidation yielded (±)-(cis-6-methyltetrahydropyran-2-yl)acetic acid in 25% yield over the two steps (Scheme 105). The yield was low due to problematic separation of the final product from chromium residues. The final product was fully characterised and the relative stereochemistry established by nOe and further confirmed by X-ray crystallography (Fig. 12 and Appendix 1).

<table>
<thead>
<tr>
<th></th>
<th>Irradiated</th>
<th>Enhanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>C(6)H</td>
<td>C(2)H, +6.5%</td>
<td></td>
</tr>
<tr>
<td>C(2)H</td>
<td>C(6)H, +6.5%</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 12: X-ray crystal structure and nOe data of (±)-(cis-6-methyltetrahydropyran-2-yl)acetic acid

Although the overall yield in the last two steps was low, the amount of the natural product prepared was sufficient to characterise it fully and confirm its structure.

The idea was to repeat this synthetic procedure using enantiomerically pure (R)-(−)-Z-5-trimethylsilylpent-4-en-2-ol (156) in the keys cyclisation step which should afford (+)-(S,S)-(cis-6-methyltetrahydropyran-2yl)acetic acid, a component of civet. Due to the lack of time this synthesis was not repeated as attention focussed on an alternative natural product.
With the synthetic methodology established, we proceeded to investigate the total synthesis of a second, more complex natural product, but one that would involve utilising similar methodology.

5.3 Synthesis of (2S, 6R)-2-Methyl-1,7-dioxaspiro[5.5]undecane

The second target compound, (2S, 6R)-2-Methyl-1,7-dioxaspiro[5.5]undecane, is a naturally occurring pheromone component of the fruit fly genus *Dacus ciliatus*.

![Fig. 12 Dacus ciliatus](image)

5.3.1 Previous syntheses of (2S, 6R)-2-Methyl-1,7-dioxaspiro[5.5]undecane

Much less is known about 160 and less synthetic effort has been placed on completing its total synthesis. However, methods for the synthesis of spiroketals are abundant.

The most common method for the synthesis of 152 and its analogues involves the alkylation of the anion of 2-benzenesulfonyltetrahydropyran with a range of different alkylating agents.\(^{192}\)

Lui has reported the one-pot conversion of 5-phenylthio-2-butanol into the title compound and related compounds in moderate yields.\(^{193}\)
However, the mercury (II) cyclisation of a dienone was found to be the most productive of all methods, giving the title compounds in 56% overall yield (Scheme 107).\textsuperscript{134}
5.3.2 Retrosynthesis

The retrosynthetic approach to 160 utilising the silyl-Prins methodology is presented in Scheme 107.

![Scheme 107]

Again, the key intermediate in the synthesis was to be a dihydropyran, 162, formed from a silyl-Prins cyclisation reaction. As in the Civet synthesis, this dihydropyran would be hydrogenated to 161 and then cyclised to the natural product. The dihydropyran would be formed from the aldehyde 163. This could be imagined being formed by an analogous route from a 1,5-diol starting material. Mono-protection and Swern oxidation would give the desired aldehyde. The pre-requisite vinylsilane 156 has already been prepared by
reduction reaction of 5-trimethylsilylpent-4-yn-2-ol, itself prepared commercially available
4-pentyn-2-ol via deprotonation and silylation.

5.4 Synthesis of (2S, 6R)-2-Methyl-1,7-dioxaspiro[5.5]undecane

The aim of this investigation was to develop a synthetic route towards 160 using the
silyl-Prins reaction.

The first stage, as before, was the preparation of 5-trimethylsilanylpent-4-yn-2-ol 156,
starting from 4-pentyn-2-ol and employing n-butyllithium and TMS-chloride, followed by
reduction of the triple bond using DIBAL.

The aldehyde component 163 for the silyl-Prins reaction was prepared from 1,5-
pentadiol. This was first mono-protected with the benzyl group. This was slightly trickier
than for propen-1,3-diol and the reaction was carried out several times before optimal
conditions for mono-protection were found. This involved using a mixed solvent of
THF:DMSO (9:1) and freshly powdered potassium hydroxide. Later investigations also
demonstrated the advantage of using benzyl bromide over benzyl chloride. Under these
conditions the targeted mono-protected 5-benzyloxypentane-1-ol 161 was obtained as a
colourless oil 28%. (Scheme 110)
The next step involved oxidation of the free hydroxyl group in the newly obtained 5-benzyloxypentan-1-ol 164 using a Swern oxidation reaction. The experiment went smoothly and the target 5-benzyloxypentan-1-al 163 was isolated 68%. (Scheme 111)

The silyl-Prins cyclisation step was carried out under conditions described previously, using indium trichloride as the Lewis acid. Thus 5-trimethylpent-4-yn-ol 156 and 163 were reacted in 1:1.5 ratio in the presence of InCl₃ (2 eq.) in dichloromethane at room temperature for 8 h to give the cyclised product 162 in 77% yield after purification. (Scheme 112)

The cis-diastereoselectivity across the oxygen atom was again confirmed by nOe, with a 7.1% enhancement observed between H(2) and H(6), similar to the enhancement observed in the previous synthesis of the civet constituent.

The synthesis was designed so that the hydroxyl protecting group could be removed at the same time as reduction of the double bond. Hydrogenation of 162 on a pre-activated Pd/C catalyst gave concomitant olefin reduction and benzyl deprotection to give the hydroxyl-tetrahydropyran 161 in 71% yield.
The final step was the cyclisation reaction. According to literature, 2,3-dichloro-5,6-dicyanobenzoquinone is an effective reagent for initiating this presumably radical cyclisation.\(^{195}\) (6-methyltetrahydropyran-2-yl)butanol 161 was treated with freshly recrystallized 2,3-dichloro-5,6-dicyano-benzoquinone. Unfortunately, this reaction did not give the desired natural product and no starting material was recovered. Had there been further time and more material, alternative cyclisation conditions, for example HgO/I\(_2\) would have been attempted.

![Scheme 114](image)

5.5 Conclusions and Future Work

The synthesis of two natural products have been attempted using cyclisation methods developed in the research group at the Open University and University of Exeter and during this thesis. The first synthesis, of (±)-(cis-6-methyltetrahydropyran-2-yl)acetic acid was successful and the natural product was obtained in good overall yield. Future work would involve repeating the reactions sequence described to perform the enantiospecific total synthesis of both the natural and unnatural forms of the product, starting from the corresponding chiral epoxide. The synthesis of the second product, (2S,6R)-2-methyl-1,7-dioxaspiro[5.5]undecane, reached an advanced stage, with a precursor to the final product being obtained. Future work would involve investigation and optimisation of the final radical cyclisation step. Although we could not achieve the cyclisation, the product obtained is a known precursor to the natural product and so this may be considered a formal synthesis of the target.

Thus we have demonstrated the efficiency and usefulness of the silyl-Prins reaction in natural product total synthesis.
Chapter 6

EXPERIMENTAL DETAILS
Chapter 6: Experimental

General

Petrol refers to the fraction boiling between 40°C and 60°C. Dichloromethane and 1,2-dichloroethane were distilled over calcium hydride. Diethyl ether, THF and toluene were distilled over sodium and benzophenone, which was used as an indicator. All other solvents were obtained anhydrous from Aldrich and used directly into the reaction vessel. All reactions were carried out under an atmosphere of nitrogen unless otherwise stated using vacuum/nitrogen manifold. All glassware, syringes and needles were pre-dried in an oven (120-140 °C) and cooled in a nitrogen atmosphere prior to use. Stirring was by internal magnetic follower. All chemicals were purified by distillation or recrystallisation where appropriate. Commercially available compounds were generally used without further purification.

All reactions were followed by TLC. Analytical thin layer chromatography was carried out using aluminum backed plates coated with Merck Kieselgel 60 GF254. Plates were visualized under UV light (at 254 nm) or by staining with acidic ceric ammonium molybdate or acidic potassium permanganate followed by heating. Flash chromatography was carried out using Matrix silica 60, 230-400 mesh; samples were applied as a saturated solution in an appropriate solvent.

Infra red (IR) spectra were recorded in the range 4000-600 cm⁻¹ using a Nicolet Magna IR 550 (Exeter) and Nicolet 205 (OU) spectrometers with internal calibration. Spectra were recorded as potassium bromide discs or as thin films between NaCl plates.

Proton (¹H) NMR spectra at 300 MHz and carbon (¹³C) NMR spectra at 75 MHz were recorded on a Bruker AV 300 (Exeter) and JEOL LAMBDA300 (OU) instruments in deuterated solvents and at 400 MHz using an Avance DEX 400 (Exeter) or JEOL EX400 (OU) instrument in deuterated solvents. NMR chemical shifts (δ) are quoted in ppm relative to an internal standard (CDCl₃). Spectroscopic data is annotated with the following abbreviations: br - broad, s - singlet, d - doublet, t - triplet, and m - multiplet. Coupling
constants, $J$, are expressed in Hz. $^1$H and $^{13}$C NMR assignments were made using COSY ($^1$H-$^1$H correlation) and HMQC ($^1$H-$^{13}$C correlation) NMR techniques.

High and low resolution mass spectra were recorded on a Kratos Profile instrument or Micromass Quattro II instrument (EPSRC Mass Spectrometry Service, Swansea) or a ThermoQuest Trace GC 2000 series or an Agilent 6890 Series GC System, Micromass GCT. Compounds characterised by high-resolution mass spectrometry were chromatographically homogenous.
Chapter 6: Experimental

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Carboethoxymethyl triphenylphosphonium bromide 15

\[
\begin{align*}
\text{Ph}_3\text{P} + \text{BrCH}_2\text{CO}_2\text{Et} & \rightarrow \text{Ph}_3\text{PCH}_2\text{CO}_2\text{Et} \ \text{Br} \\
\text{C}_{18}\text{H}_{15}\text{P} & \rightarrow \text{C}_{22}\text{H}_{22}\text{BrO}_2\text{P} \\
\text{Mol. Wt.:} 262.29 & \text{Mol. Wt.:} 348.11
\end{align*}
\]

Ethyl bromoacetate (8.35 g, 50 mmol) was added dropwise to triphenylphosphine 3 (13.10 g, 50 m mol) in dry toluene (50 ml). The mixture was stirred for 30 min at room temperature and then heated for another 30 min on a water bath. After cooling, it was filtered, washed with toluene (2 x 20 ml), hexane (2 x 25 ml), the solvents removed in vacuo and the solid precipitate dried in an oven overnight. The target compound, carboethoxymethyltriphenylphosphonium bromide 15 was isolated as white solid mass. (18.61 g, 87%). $\delta_\text{H} (300 \text{ MHz; CDCl}_3) 7.93-7.60 (15\text{H, m, 3Ar}), 5.58 (2\text{H, d, J}_\text{PH} 13.7, \text{CH}_2\text{CO}_2\text{Et}), 4.01 (2\text{H, q, J}_7 7.1, \text{CO}_2\text{CH}_2\text{CH}_3), 1.04 (3\text{H, t, J}_7 7.1)$. All other data were in agreement with previously reported values.\textsuperscript{8}

Carboethoxymethylene triphenylphosphorane 16

\[
\begin{align*}
\text{Ph}_3\text{PCH}_2\text{CO}_2\text{Et} \rightarrow \text{Ph}_3\text{PCH}_2\text{CO}_2\text{Et} \\
\text{C}_{18}\text{H}_{15}\text{BrO}_2\text{P} & \rightarrow \text{C}_{22}\text{H}_{22}\text{O}_2\text{P} \\
\text{Mol. Wt.:} 429.29 & \text{Mol. Wt.:} 348.11
\end{align*}
\]

Carboethoxymethyltriphenylphosphonium bromide 15 (18.61 g, 43 mmol) was dissolved in a biphasic solution of cold water (150 ml) and dichloromethane (120 ml). The mixture was stirred vigorously and sodium hydroxide (50 ml, 0.1 M solution) added over a period of 5 min. After stirring for a further 10 min, was checked for alkalinity by pH paper. The layers were then separated and the aqueous layer washed with dichloromethane (3 x 40 ml), the organic layers combined, dried over magnesium sulfate and excess solvent removed in vacuo. To the resulting syrup was added warm petroleum (~55 ml) and dichloromethane (10 ml) and stirred for 15 min. On cooling to 0 °C, white crystals formed which were
filtered and dried to give carboethoxymethylenetriphenylphosphorane 16 (8.84 g, 58%). This was used immediately in the Wittig reaction without further purification or analysis.

3-Phenyl-acrylic acid ethyl ester 17

Carboethoxymethylenetriphenylphosphorane 16 (8.84 g, 25 mmol) was slowly dissolved in dichloromethane (70 ml). After 20 min a solution of phenylacetaldehyde (2.65 g, 25 mmol) in dichloromethane (25 ml) was added, stirred for 30 min and then the solvent was removed on vacuo. The residue was dissolved in warm petrol and refluxed for 20 min on a water bath. After cooling to room temperature the mixture was filtered and the solvent removed in vacuo. To the obtained thick liquid was added light petroleum (25 ml) and a pinch of silica gel, the contents stirred for further 10 min, then filtered, and the solvent removed to give pure 17 (2.34 g, 60%). $\delta_H$ (300 MHz; CDCl$_3$) 8.03 (1H, d, $J$ 15.9, PhCH=CH), 7.40 (5H, m, Ar), 6.33 (1H, d, $J$ 15.9, PhCH=CH), 4.15 (2H, q, $J$ 7.2, OCH$_2$CH$_3$), 1.24 (3H, t, $J$ 7.1, OCH$_2$CH$_3$). All other data were in agreement with previously reported values.

Butyltriphenylphosphonium bromide 18

Triphenylphosphine 3 (26.20 g, 0.1 mol) and 1-brombutane (27.00 g, 0.2 mol) were stirred together for 2 h at 100-110 °C. The flask was then cooled to room temperature and transferred to an ice/water bath. After crystallisation was completed, the solution was then filtered, the solid rinsed with portions of petrol and the solvent removed in vacuo. Butyltriphenylphosphonium bromide 18 was obtained (10.70 g, 26 %). $\delta_H$ (300 MHz;
Under a nitrogen atmosphere, to butyltriphenylphosphonium bromide 18 (8.20 g, 20 mmol) was added the solution of potassium t-butoxide (2.50 g, 22 mmol) in dry tetrahydrofuran (50 ml) and the mixture was stirred for 40 min. Over this time the light yellow colour turned to bright red. Then a solution of 2,4-dichlorobenzaldehyde (3.50 g, 20 mmol) in dry tetrahydrofuran (15 ml) was added over 5 min, the reaction flask being cooled in an ice/water bath. The solution changed of the colour to grey. The mixture was filtered and the precipitate was washed with warm petrol (3 × 20 ml). The layers were combined, ~20 ml hexane was added together with a pinch of silica gel. This mixture was stirred for 5 min, filtered and the solvent removed in vacuo. A thick syrup of inseparable E and Z isomers of 19 was obtained (2.24 g, 52%). \( \delta_H \) (300 MHz; CDCl\(_3\)) 7.33-6.98 (6H, m, overlapping Ar), 6.55 (1H, d, \( J \) 14.2, Cl\(_2\)PhCH\(_{2}\)=CH), 6.30 (1H, d, \( J \) 8.0, Cl\(_2\)PhCH\(_{2}\)=CH), 6.04 (1H, br m, Cl\(_2\)PhCH=CH\(_2\)), 6.67 (1H, m, Cl\(_2\)PhCH=CH\(_2\)), 2.12-1.97 (4H, m, overlapping 2 × CH=CHCH\(_2\)CH\(_2\)), 1.41-1.24 (4H, m, overlapping 2 × CH=CHCH\(_2\)CH\(_2\)), 0.86-0.74 (6H, m, overlapping 2 × CH\(_3\)). All other data were in agreement with previously reported values.\(^{58}\)
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4-(Tridecafluorohexyl)bromobenzene 22

A solution of copper powder (2.94 g, 0.046 mol), 2,2'-bipyridine (0.23 g, 1.47 \times 10^{-3} \text{ mol}), 4-bromoiodobenzene 21 (5.96 g, 0.021 mol), DMSO (20 ml) and hexafluorobenzene (30 ml) was added dropwise over 3 h to a solution of iodoperfluorohexane (9.39g, 0.021 mol) in hexafluorobenzene (15 ml) at 70 °C. The mixture was subsequently stirred at 70 °C for 72 h before it was poured into a beaker containing dichloromethane and water (50-50 ml). After filtering, the organic layer was separated, washed with water (3 \times 25 ml) and dried over CaCl₂. After concentration to ~15-20 ml, the crude product was extracted into perfluoro-1,3-dimethylcyclohexane (3 \times 10 ml) and the solvent removed in vacuo. Distillation under reduced pressure (bp 75-78 °C/0.1mmHg) gave the product as a colourless liquid 22, but never completely free from contaminants. (4.59g, 46%). δH (400 MHz; CDCl₃) 7.64 (2H, d, \(J = 8.2\), 3,5-ArH), 7.44 (2H, d, \(J = 8.5\), 2,6-ArH); m/z Cl 476 [(M)+, C₁₂H₄¹¹BrF₁₃, 98%], 474 [(M)+, C₁₂H₄⁹⁷BrF₁₃, 100%]; All other data were in agreement with previously reported values.⁴⁴

Tris(4-tridecafluorohexylphenyl)phosphine 4: Method 1

\(n\)-Butyllithium (3.50 ml, 2.5 M solution in hexane) in diethyl ether (15 ml) was added dropwise over 1 h to impure 4-(tridecafluorohexyl)bromobenzene 22 (4.00 g, 8.4 mmol) in diethyl ether (40 ml) at −78 °C and then stirred at this temperature for a further 1 h. The
temperature was raised to room temperature and the reaction stirred for 1 h, after which it was cooled back to \(-78^\circ C\) and phosphorus trichloride (0.24 ml, 2.6 mmol) in diethyl ether (15 ml) added dropwise over 1 h. The reaction mixture was allowed to warm slowly to room temperature with continuous stirring over a 12 h period. The mixture was hydrolysed with 10% aqueous NH\(_4\)Cl (50 ml), the organic layer separated, washed with water (2 \times 15 ml) and dried over MgSO\(_4\). The organic phase was concentrated in vacuo to 10 ml and passed quickly through an alumina column, using petrol as eluent. After the solvent was removed the crude product was subject to flash chromatography (hexane : ethyl acetate 1:4), but gave no identifiable material.

**Tris(4-tridecafluorohexylphenyl)phosphine 4: Method 2**

A mixture of tris(4-bromophenyl)phosphine 23 (2.00 g; 4 mmol), copper powder (1.68 g, 26 mmol) and 2,2'-bipyridine (0.13 g, 0.84 mmol) in hexafluorobenzene (10 ml) was added dropwise over 2 h to a solution of iodoperfluorohexane (5.35 g, 12 mmol) in hexafluorobenzene (15 ml) at 75°C. The mixture was stirred at this temperature for 72 h. After cooling to room temperature, it was hydrolysed with 10% aqueous NH\(_4\)Cl (30 ml), the organic layer collected, washed with water (2 \times 10 ml) and dried over MgSO\(_4\). The organic phase was concentrated in vacuo to 8-10 ml and passed quickly through an alumina pad, using petrol as eluent. After the solvent was removed the crude product was chromatographed on a silica gel column (ethyl acetate: hexane 1:4) to give unidentifiable material.

**Tris(4-tridecafluorohexylphenyl)phosphine 4: Method 3**

A mixture of tris(4-bromophenyl)phosphine 23 (2.00 g; 4 mmol), copper powder (1.68 g, 26 mmol) and 2,2'-bipyridine (0.13 g, 0.84 mmol) in hexafluorobenzene (10 ml) was added dropwise over 2 h to a solution of iodoperfluorohexane (5.35 g, 12 mmol) in hexafluorobenzene (15 ml) at 75°C. The mixture was stirred at this temperature for 72 h. After cooling to room temperature, it was hydrolysed with 10% aqueous NH\(_4\)Cl (30 ml), the organic layer collected, washed with water (2 \times 10 ml) and dried over MgSO\(_4\). The organic phase was concentrated in vacuo to 8-10 ml and passed quickly through an alumina pad, using petrol as eluent. After the solvent was removed the crude product was chromatographed on a silica gel column (ethyl acetate: hexane 1:4) to give unidentifiable material.
A mixture of tris(4-tridecafluorohexylphenyl)phosphine oxide 6 (0.50 g, 0.4 mmol), trichlorosilane (0.2 ml, 2 mmol), triethylamine (0.42 ml, 3 mmol) and toluene (12 ml) was stirred at reflux for 6 h under nitrogen. After cooling to room temperature, a saturated aqueous solution of potassium hydrogen carbonate (1 ml) was added and the mixture stirred for 5 min at room temperature. The solution was filtered through a pad of alumina and washed with toluene (3 x 30 ml) and evaporated under reduced pressure to give the crude product as a white solid. The desired product was subject to column chromatography on silica (ethyl acetate:hexane 1:4) but gave unidentifiable material.

**Tris(4-chlorophenyl)phosphine oxide 26**

\[
\text{C}_{18}H_{12}Cl_3P \quad \text{Mol. Wt.: 365.62}
\]

\[
\text{C}_{18}H_{12}Cl_3OP \quad \text{Mol. Wt.: 381.62}
\]

To a solution of tris(4-chlorophenyl)phosphine 25 (3.00 g, 8.2 mmol) in diethyl ether (80 ml) was added dropwise a solution of 35% solution of hydrogen peroxide (0.28 g, 8.2 mmol) in diethyl ether (20 ml). The solution was heated to reflux for 3 h. After cooling, the solution was filtered and dissolved into minimum amount of toluene and 0.3 M solution sodium hydroxide (10 ml) added. The layers were separated and the organic layer dried (MgSO₄), filtered and evaporated *in vacuo* to give the product 26 as white crystals (3.12 g, 99%) \( \nu_{\text{max}}/\text{cm}^{-1} \) (KBr) 1590, 1480, 1195 (P=O), 1020, 995, 760 (C-Cl); all other data in agreement with literature values.\(^{59}\)
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**Tris(4-tridecafluorohexylphenyl)phosphine oxide 6**

![Diagram]

A mixture of *tris*(4-chlorophenyl)phosphine oxide 26 (1.00 g, 2.62 mmol), perfluorohexyl iodide (3.75 g, 8.4 mmol), copper powder (1.20 g, 18.6 mmol), 2,2'-bipyridine (0.82 g, 0.53 mmol) and DMSO (40 ml) was stirred at 120 °C for 36 h. After cooling to room temperature, the reaction mixture was diluted with chloroform and water (90 : 90 ml), filtered through a pad of celite and washed with chloroform (2 x 40 ml). The organic layer was separated, washed with 1M hydrochloric acid (2 x 100 ml), water (2 x 100 ml) and brine (100 ml), dried over magnesium sulfate and evaporated under reduced pressure to give the crude product, which could not be identified.

**Tris(4-bromophenyl)phosphine 23**

A solution of n-butyllithium (2.82 ml of 2.5 M in hexane) in diethyl ether (20 ml) at −78 °C was added from a dropping funnel to a solution of 4-bromoiodobenzene 21 (2.00 g, 7 mmol) in dry diethyl ether (30 ml) at −78 °C and stirred for 1 h. The temperature was raised to ambient temperature for 1 h and then cooled again to −78 °C and phosphorus trichloride (0.2 ml, 2.3 mmol) in diethyl ether (10 ml) added dropwise over 1 h. The reaction mixture was allowed to warm slowly to room temperature with continuous stirring over a 12 h period. The mixture was hydrolysed with 10 % aqueous NH₄Cl (2 x 25 ml), the organic layer separated, washed with water (3 x 15 ml) and dried over MgSO₄. The organic phase was concentrated *in vacuo* to 10 ml and passed quickly through an alumina
column, using petrol as eluent. After the solvent was removed the product 23 formed as white crystals with yield of 87%. (1.01 g, 2.0 mmol). This reaction was performed on various scales, using 6, 10 and 20 g of 4-bromoiiodobenzene; yields of 86%, 84% and 79%, respectively, were obtained. \( \delta_H \) (400 MHz; CDCl₃) 7.41 (6H, d, \( J = 7.9, 3 \times 3,5\)-ArH), 7.05 (6H, d, \( J = 7.9, 3 \times 2,6\)-ArH); \( m/z \) CI 499 [(M)+, C₁₈H₁₂Br₃P, 98%], 497 [(M)+, C₁₈H₁₂Br₃P, 100%]. All other data were in agreement with previously reported values.

\[ \text{Jm(4-bromophenyl)phosphine oxide 27} \]

\[
\begin{align*}
P\left(\begin{array}{c}
\text{Br} \\
\end{array}\right)_{3} & \xrightarrow{\text{H₂O₂, Et₂O}} \text{O=P}\left(\begin{array}{c}
\text{Br} \\
\end{array}\right)_{3} \\
\text{C₁₈H₁₂Br₃P} & \text{Mol. Wt.: 498.97} \\
\text{C₁₈H₁₂Br₃OP} & \text{Mol. Wt.: 514.97}
\end{align*}
\]

Hydrogen peroxide (2.74 ml 35% solution) was added dropwise to \textit{tris}(4-bromophenyl)phosphine 23 (5 g, 0.1 mol) in diethyl ether (90 ml) and the solution heated to reflux for 2 h. After cooling, the solution was filtered and the solid dissolved into a minimum amount of toluene to which 0.3 M sodium hydroxide (~10 ml) was added. The organic layer was separated, dried over MgSO₄, filtered and evaporated \textit{in vacuo} to give the product 27 as white crystals. (3.39 g, 65%). \( \nu_{\text{max/cm}^{-1}} \) (KBr) 1590, 1480, 1200 (P=O), 1010, 740 (C-Br); \( \delta_H \) (300 MHz; CDCl₃) 7.57 (6H, d, \( J = 8.04, 3 \times 2,6\)-ArH), 7.41 (6H, d, \( J = 8.04, 3 \times 2,6\)-ArH). All other data were in agreement with previously reported values.

\[ \text{Jm(4-tridecafluorohexylphenyl)phosphine oxide 6} \]

\[
\begin{align*}
\text{O=P}\left(\begin{array}{c}
\text{Br} \\
\end{array}\right)_{3} & \xrightarrow{1. \text{CuF}_{13}, 2. \text{Cu}, 3. 2,2'-\text{bipyridine}, 4. \text{DMSO}} \text{O=P}\left(\begin{array}{c}
\text{C}_{13} \text{F}_{12}\text{Br}_{3}\text{OP} \\
\end{array}\right)_{3} \\
\text{C₁₈H₁₂Br₃OP} & \text{Mol. Wt.: 514.97} \\
\text{C₁₈H₁₂Br₃OP} & \text{Mol. Wt.: 1232.39}
\end{align*}
\]

A mixture of \textit{tris}(4-bromophenyl)phosphine oxide 27 (1.00 g, 1.94 mmol), perfluoroheptyliodide (2.77 g, 6.2 mmol), copper powder (0.88 g, 13.7 mmol), 2,2'-bipyridine (60 mg,
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0.38 mmol) and DMSO (40 ml) was stirred at 120 °C for 36 h. After cooling to room temperature the reaction mixture was diluted with chloroform and water (90:90 ml), filtered through a pad of celite and washed with chloroform (2 × 40 ml). The organic layer was separated, washed with 1M hydrochloric acid (2 × 100 ml), water (2 × 100 ml) and brine (100 ml), dried over magnesium sulfate and evaporated under reduced pressure to give the crude product, which upon recrystallisation from ethanol yielded the compound as colourless needles 24 (1.09 g, 46%). δF (400 MHz; CDCl3) -81.0 (CF₃), -111.5 (CF₂), -121.6 (CF₂), -121.8 (CF₂), -123.0 (CF₂), -126.4 (CF₂); m/z Cl 1232 [(M)+, C₃₆H₁₂F₃₉PO, 100%]; No other data was detected. This experiment was repeated several times, but without success.

**Tris[4-(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)phenyl]phosphine 28**  

\[
\begin{align*}
\text{Br} & \quad \text{P} \\
\text{C}_6\text{H}_2\text{Br}_3\text{P} & \quad \text{C}_6\text{H}_2\text{Br}_3\text{P} \\
\text{Mol. Wt.:} & \quad 498.97 & \quad \text{Mol. Wt.:} & \quad 1304.58
\end{align*}
\]

A mixture of **tris(4-bromophenyl)phosphine 23** (1.00 g, 1.94 mmol), 1,1,2,2-tetrahydroperfluorooctyl iodide (2.90 g, 6 mmol), copper powder (0.88 g, 13.7 mmol), 2,2'-bipyridine (0.06 g, 0.38 mmol) and DMSO (30 ml) was stirred at 120 °C for 96 h. After cooling to room temperature the reaction mixture contained only starting materials.

**Tris[4-(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)phenyl]phosphine oxide 29**  

\[
\begin{align*}
\text{Br} & \quad \text{P=O} \\
\text{C}_6\text{H}_2\text{Br}_3\text{OP} & \quad \text{C}_6\text{H}_2\text{Br}_3\text{OP} \\
\text{Mol. Wt.:} & \quad 514.97 & \quad \text{Mol. Wt.:} & \quad 1318.55
\end{align*}
\]
A mixture of tris(4-bromophenyl)phosphine oxide 27 (0.50 g, 1 mmol), 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl iodide (1.50 g, 3 mmol), copper powder (0.15 g, 2.19 mmol), 2,2'-bipyridine (0.11 g, 0.07 mmol) and DMSO (40 ml) was stirred at 120 °C for 36 h. After cooling to room temperature, the reaction mixture was diluted with chloroform and water (90:90 ml), filtered through a pad of celite and the pad washed with chloroform (2 x 40 ml). The organic layer was separated, washed with 1 M hydrochloric acid (2 x 100 ml), water (2 x 100 ml) and brine (100 ml), dried over magnesium sulfate and evaporated under reduced pressure to give no identifiable material.

Tris(4-methoxyphenyl)phosphine oxide 30

To a solution of tris(4-methoxyphenyl)phosphine (1.00 g, 2.8 mmol) in dichloromethane (30 ml) was added dropwise a solution of 35% solution of hydrogen peroxide (0.48 g, 14.2 mmol) in dichloromethane (20 ml) and the mixture heated to reflux for 5 h. After cooling, the solution was filtered and dissolved into minimum amount of toluene and 0.3 M solution of sodium hydroxide (10 ml) was added. The layers were separated and the organic layer dried over MgSO₄, filtered and evaporated in vacuo to give the product 30 as white crystals (0.76 g, 66%); ν_max/cm⁻¹ (KBr) 3100, 1550, 1440, 1120 (P=O), 1005, 820; δ_H (300 MHz; CDCl₃) 7.52 (6H, m, 3 x 2,6 ArH), 6.90 (6H, d, J 9.4, 3 x 3,5 ArH), 3.72 (9H, s, 3 x CH₃); δ_C (300 MHz; CDCl₃) 126.2 (3 x C-P), 133.7 (3 x 2,6-ArC), 124.0 (3 x C-O), 113.8 (3 x 3,5-ArC), 55.2 (3 x CH₃).
**Tris(4-hydroxyphenyl)phosphine oxide 31**

![Chemical structure of 31](image)

A solution of tris(4-hydroxyphenyl)phosphine oxide 30 (0.05 g, 1.37 mmol) in dichloromethane (15 ml) was cooled to -78°C and a 1M solution of boron tribromide in dichloromethane (7.8 ml, 7.8 mmol) added dropwise over a 10 min period. The solution was stirred for a further 24 h at room temperature and then poured into a mixture of ice/water (150 ml), stirred for 15 min and mixture then heated to 55-60°C. The mixture was extracted with ethyl acetate (5 × 100 ml), the organic layers collected, washed with water (3 × 40 ml), dried over MgSO₄, then filtered and evaporated. The crude oil was dissolved in a minimum amount of ethyl acetate, warmed and filtered into a round-bottomed flask that was placed in an ice/water bath. No crystals were obtained. The solvent was evaporated and the brown oil checked by NMR. No identifiable signals were seen.

**Tris(pentafluorophenyl)phosphine 33**

![Chemical structure of 33](image)

A solution of n-butyllithium (2.8 ml of 2.5 M in hexane) in diethyl ether (20 ml) at -78 °C was added from a dropping funnel to a solution of iodoperfluorobenzene 32 (2.00 g, 6.8 mmol) in dry diethyl ether (10 ml) at -78 °C. The mixture was stirred for 1 h, the temperature raised to ambient for 1 h and then cooled again to -78 °C. Phosphorus
trichloride (0.20 ml, 2.3 mmol) was added dropwise in diethyl ether (10 ml) over 1 h. The reaction mixture was allowed to warm slowly to room temperature with continuous stirring over 12 h. The mixture was hydrolysed with 10% aqueous NH₄Cl (2 x 25 ml), the organic layer separated, washed with water (3 x 25 ml) and dried over MgSO₄. The organic phase was concentrated in vacuo to 10 ml and passed quickly through an alumina column, using 40-60 °C light petroleum as eluent. After the solvent was removed the product 33 formed as white crystals with yield of 59%, 0.71 g. m/z (Cl) 532 [(M)+, C₁₈F₁₅P, 71%], 365 [(M)+, -C₆F₅, 55%], 198 [(M)+, -(C₆F₅)₂, 20%], 129 [(M)+, 100%]; All other data were in agreement with previously reported values.⁴⁴

**Carboethoxymethyl tris(pentafluorophenyl)phosphonium bromide 34**

![Chemical structure of 34](image)

To tris(pentafluorophenyl)phosphine 33 (2.00 g, 3.76 mmol) in dry toluene (40 ml) was added dropwise ethyl bromoacetate (0.63 g, 3.76 mmol). The mixture was stirred for 72 h, but within this period the reaction was not complete, so was decided to stop it.

**1H,1H,2H,2H-Perfluoroctyl chloroformate 35**

Note to future readers: Special precautions should be observed when handling phosgene; refer to MSDS and perform full risk & COSHH assessment.

![Chemical structure of 35](image)
Perfluoroctanol 34 (5 g, 13.74 mmol) in dry THF (40 ml) was added to a solution of phosgene in toluene 20% (11.3 ml, 22.72 mmol) in dry THF (50 ml) at 0 °C under nitrogen. The solution was stirred for 2 h and then the ice bath removed. The solution was stirred at room temperature for 8 h and then heated at reflux temperature for 48 h. The solvent was then removed in vacuo giving the fluorous chloroformate as a pale yellow oil, which was used in the next step without further purification.

1H,1H,2H,2H-Perfluoroctyl hydrazine-1,2-dicarboxylate 36

\[
\begin{align*}
\text{C}_9\text{H}_4\text{CIF}_3\text{O}_2 & \quad \text{Cl} \\
\text{C}_6\text{H}_{13}\text{F}_3\text{Cl} & \quad \text{NH}_2\text{NH}_2\text{H}_2\text{O} \\
\text{N} & \quad \text{Cl} \\
\text{N} & \quad \text{O} \\
\text{C}_9\text{H}_4\text{CIF}_3 & \quad \text{O} \\
\text{C}_6\text{H}_{13}\text{F}_3\text{Cl} & \quad \text{H}
\end{align*}
\]

Md. Wt.: 426.56 Md. Wt.: 812.24

The fluorous chloroformate 35 (3.49 g, 8.2 mmol) in ethanol (15 ml) was cooled to 0 °C and two solutions of hydrazine hydrate (0.41 g, 8.2 mmol) in ethanol (5 ml) and sodium carbonate (0.87 g, 8.2 mmol) in water (20 ml) added simultaneously and dropwise. The ice bath was then removed and the solution stirred at room temperature for 2 h. The hydrazine was formed as a white precipitate, which was removed by filtration. The white solid was re-crystallised in ethanol to give the hydrazine 36 as white crystals (2.68 g, 81% over the 2 steps). Mp 104 °C; Rf 0.42 (hexane:EtOAc 1:1). Found [M+H]^+ 813.0304; C_{18}H_{10}F_{26}N_2O_4 requires 813.0347. δmax/cm⁻¹ (KBr) 3293 (NH), 3053 (CH), 2351, 1731 (C=O), 1201 (CF); δH (300 MHz; CDCl₃) 6.35 (2H, s, NH), 4.41 (4H, t, J 7, CO₂CH₂), 2.40 (2H tt, J 6, 12, CH₂CF₂); δC NMR (acetone-d⁶) 156.2, 121.4-108.3 (m), 57.2, 30.2 (t, J=21.2 Hz); δF NMR -80.6 (6F), -112.9 (4F), -121.4 (4F), -122.4 (4F), -123.0 (4F), -126.3 (4F).
The fluorous hydrazine 36 (2.00 g, 2.46 mmol) and pyridine (0.4 ml, 4.92 mmol) were dissolved in dichloromethane (25 ml) and the mixture cooled to 0 °C. N-Bromosuccinimide (0.86 g, 4.8 mmol) was added slowly. The ice bath was removed after addition and the reaction stirred vigorously at room temperature for 2 h. The reaction mixture was then diluted with dichloromethane (150 ml) and washed thoroughly with aqueous sodium sulfite solution (3 × 20 ml), sodium hydrogenbicarbonate (3 ×20 ml), brine (3 ×20 ml) and water (3 ×20 ml). The organic layer was dried over magnesium sulfate and the solvent removed in vacuo to give fluorous DEAD 37 as a yellow solid (0.35 g, 92%). mp 61 °C; νmax/cm⁻¹ (KBr) 3052 (CH), 1771 (C=O), 1211 (CF); δH (acetone-d6) 4.87 (t, J = 5.9 Hz, 4H), 2.91 (tt, J = 5.9, 19, 4H); δC (acetone-d6) 161.2, 125–104 (m), 62.7, 31.3 (t, J = 21.1); δF (acetone d6) δ = 80.6 (6F), -112.9 (4F), -121.3 (4F), -122.3 (4F), -123 (4F), -123.6 (4F), -125.7 (4F); m/z 812 (M<formula>+</formula>2, 55%), 449 (91%), 327 (85%), 131 (100%).

Method for Determining of Partition Coefficients

Fluorous hydrazine 36 (~20 mg) was dissolved in a mixture of organic solvent (2 ml) and fluorous solvent (2 ml). The mixture was stirred for 22 h at room temperature and then allowed to stand for 1 h. Upon settling a 0.4 ml aliquot was taken from each layer and added to dodecane in hexane (2 ml, 0.0001 M). Each fraction was then analysed by GC (7 injections) and partition coefficients calculated for each pair of solvents tested.
Method 1: Employing DEAD

Triphenylphosphine (2.62 g, 10 mmol) and ethanol (0.69 g, 11 mmol) in diethyl ether (10 ml) were added dropwise to a stirred solution of DEAD (1.74 g, 11.1 mmol) and benzoic acid (1.22 g, 10 mmol) in diethyl ether under nitrogen. The solution was stirred at room temperature overnight. The white precipitate formed was removed by filtration and the solvent removed in vacuo. The residue was purified by flash chromatography (hexane:EtOAc 1:1) to give the title compound (1.30 g, 85%); δH (300 MHz; CDCl₃) 8.03 (2H, d, J = 7, CH₃), 7.64 (2H, t, J = 6.0, CH₃), 7.40 (1H, t, J = 7, CH₃), 4.15 (3H, t, J = 8.9, CH₃), 1.27 (2H, q, J = 8.9, CH₂); all other data in agreement with literature values.

Method 2: Employing Solid-Supported Triphenylphosphine

As per method 1, except on 1/10th scale and with the following modifications: the solid supported triphenylphosphine (0.50 g, 1.5 mmol) was swelled in dichloromethane (2 ml) for 5 h before adding ethanol (0.069 g, 1.1 mmol). A solution of DEAD (0.261 g, 1.5 mmol) and benzoic acid (018 g, 1.5 mmol) in DCM was then added and the solution shaken for 72 h. The solid supported reagent was removed by filtration, the solvent removed in vacuo and the product purified by chromatography as before (0.77 g, 52%). All data as reported previously.

Method 3: Employing FDEAD

As per method 1, except on 1/10th scale and using FDEAD (0.89 g, 1.1 mmol) in place of DEAD and using THF as the reaction solvent. After 24 h, the reaction mixture was
extracted with FC-72 (3 x 20 ml) to remove the fluorous-hydrazine. The THF layer was evaporated and the residue analysed by $^1$H and $^{19}$F nmr, which showed no fluorine-containing compound(s). The product was then purified by flash chromatography (0.125 g, 84 %) to give the *title compound*; data as reported previously.

**i-Propyl Benzoate**

\[
\text{C}_7\text{H}_8\text{O}_2\quad \text{ Molecular weight:} 122.12
\]

\[
\text{H}_2\text{C}_8\text{O}_2\quad \text{ Molecular weight:} 184.20
\]

**Method 1: Employing DEAD**

Triphenylphosphine (2.62 g, 10 mmol) and isopropanol (0.66 g, 11 mmol) in diethyl ether (10 ml) were added dropwise to a stirred solution of DEAD (1.74 g, 11.1 mmol) and benzoic acid (1.22 g, 10 mmol) in diethyl ether under nitrogen. The solution was stirred at room temperature overnight. The white precipitate formed was removed by filtration and the solvent removed *in vacuo*. The residue was purified by flash chromatography (hexane:EtOAc 1:1) to give the *title compound* (1.40 g, 78%); $\delta$H (300 MHz; CDCl$_3$) 8.31 (2H, d, $J = 7$, CH$_A$), 7.98 (2H, t, $J = 6.0$, CH$_B$), 7.65 (1H, t, $J = 7$, CH$_C$), 5.21 (1H, m, OCHCH$_3$), 1.22 (6H, d, $J = 8.6$, 2 x CH$_3$); all other data in agreement with literature values.

**Method 2: Employing Solid-Supported Triphenylphosphine**

As per method 1, except on 1/10$^\text{th}$ scale and with the following modifications: the solid supported triphenylphosphine (0.50 g, 1.5 mmol) was swelled in dichloromethane (2 ml) for 5 h before adding isopropanol (0.066 g, 1.1 mmol). A solution of DEAD (0.17 g, 1.1 mmol) and benzoic acid (0.18 g, 1.5 mmol) in DCM was then added and the solution shaken for 72 h. The solid supported reagent was removed by filtration, the solvent removed *in vacuo* and the product purified by chromatography as before. All data as reported previously.
Method 3: Employing $^F$DEAD

As per method 1, except on $1/10^{th}$ scale and using $^F$DEAD (0.89 g, 1.1 mmol) in place of DEAD and using THF as the reaction solvent. After 24 h, the reaction mixture was extracted with FC-72 (3 x 20 ml) to remove the fluorous-hydrazine. The THF layer was evaporated and the residue analysed by $^1$H and $^{19}$F nmr, which showed no fluorine-containing compound(s). The product was then purified by flash chromatography (1.19 g, 73 %) to give the title compound; data as reported previously.

(5)-(-)-N-1-Phenylbutoxyphthalimide$^{66,196}$

\[
\begin{align*}
\text{C}_{10}H_{10}NO_3 & \quad \text{Mol. Wt.: 183.13} \\
\text{C}_{12}H_{19}O & \quad \text{Mol. Wt.: 138.19} \\
\text{C}_{14}H_{17}NO_2 & \quad \text{Mol. Wt.: 295.33}
\end{align*}
\]

Method 1: Employing DEAD

$N$-Hydroxyphthalimide (0.34 g, 2.24 mmol) was added to a solution of triphenylphosphine (0.58 g, 2.22 mmol) and (R)-1-phenylbutanol (0.15 g, 1 mmol) in THF (20 ml) under nitrogen. DEAD (0.35 ml, 2.24 mmol) in THF (10 ml) was added slowly with stirring. The resulting mixture was heated at 50 °C for 72 h. After cooling, the solvent was removed in vacuo and the residue purified by chromatography (hexane:EtOAc 2:1) to give the title compound as a white solid (0.53 g, 81%). $\delta_H$ (300 MHz; CDCl$_3$) 7.70 (4H, m, Ar), 7.45 (2H, m, Ar), 5.34 (1H, t, $J = 7.0$, OCH), 2.16 (1H, m, CHCH$_2$), 1.91, (1H, m, CHCH$_2$), 1.47 (2H, m, CH$_2$Me), 0.97 (3H, t, $J = 7.4$, Me); $[\alpha]_D^{22} = -187.2$ (c 2, CH$_2$Cl$_2$); >95%ee by NMR (Eu(hfc)$_3$ doping); all other data in agreement with literature values. (I would like to thank and acknowledge Professor Chris Moody, University of Exeter, for supplying experimental details and copies of spectra for comparison).$^{196}$
Method 2: Employing Solid-Supported Triphenylphosphine

As per method 1, with the following modifications: the solid supported triphenylphosphine (1.0 g, 3 mmol) was swelled in dichloromethane (2 ml) for 5 h before adding (R)-1-phenylbutanol (0.15 g, 1 mmol). A solution of DEAD (0.35 ml, 2.24 mmol) and N-hydroxyphthalimide (0.34 g, 2.24 mmol) in DCM was then added and the solution shaken for 72 h. The solid supported reagent was removed by filtration, the solvent removed in vacuo and the product purified by chromatography as before (0.14 g, 50%). All data as reported previously.

Method 3: Employing "DEAD"

As per method 1, except using "DEAD (1.81 g, 2.24 mmol) in place of DEAD and using THF as the reaction solvent. After 72 hours, the reaction mixture was extracted with FC-72 (3 x 20 ml) to remove the fluorous-hydrazine. The THF layer was evaporated and the residue analysed by $^1$H and $^{19}$F nmr, which showed no fluorine-containing compound(s). The product was then purified by flash chromatography (1.27 g, 78 %) to give the title compound; data as reported previously.

i-Propyl 3,5-dinitrobenzoate

![Chemical Structure](image)

Method 1: Employing DEAD

Triphenylphosphine (2.62 g, 10 mmol) and isopropanol (0.6 g, 10 mmol) in THF (2 ml) were added dropwise to a stirred solution of DEAD (1.91 g, 11 mmol) and 3,5-dinitrobenzoic acid (2.48 g, 11 mmol) in THF under nitrogen. The solution was stirred at room temperature overnight. The white precipitate formed was removed by filtration and
the solvent removed \textit{in vacuo}. The residue was purified by flash chromatography (hexane:EtOAc 1:1) to give the \textit{title compound} (2.33 g, 92%); $\delta_{H}$ (300 MHz; CDCl$_3$) 9.15 (1H, brtr, Ar), 9.08 (2H, m, Ar), 5.30 (1H, m, OCH), 1.37 (6H, d, $J = 6.1$, 2 x CH$_3$); all other data in agreement with literature values.

**Method 3: Employing $^5$DEAD**

As per method 1, except on 1/10$^{th}$ scale and using $^5$DEAD (0.89 g, 1.1 mmol) in place of DEAD. After 24 hours, the reaction mixture was extracted with FC-72 (3 x 20 ml) to remove the fluorous-hydrazine. The THF layer was evaporated and the residue analysed by $^1$H and $^{19}$F nmr, which showed no fluorine-containing compound(s). The product was then purified by flash chromatography (0.24 g, 91%) to give the \textit{title compound}; data as reported previously.

**The Preparation of InCl$_3$SiO$_2$ catalyst$^{68}$**

Silica gel (6.00 g, 100 mmol, Aldrich, 230-400 mesh) was added to a stirred solution of indium trichloride (0.19 g, 0.9 mmol) in acetonitrile (8 ml), and left overnight after which time the solvent was evaporated \textit{in vacuo}. The catalyst was stored under nitrogen and could be kept indefinitely.

\textit{N-(2,4,6-Trimethoxyphenyl)hydrazinecarboxylic acid ethyl ester 39.$^{69}$ (Conventional method)}

![Chemical Structures](image)

A mixture of 1,3,5-trimethoxybenzene 38 (0.84 g, 5 mmol), DEAD (0.87 g, 5 mmol) and freshly prepared InCl$_3$SiO$_2$ (0.14 g, 0.5 mmol) in 1,2-dichloroethane (10 ml) was stirred at
reflux for 10 h. The reaction mixture was diluted with water (20 ml) and extracted with chloroform (3 × 15 ml). The organic layers were combined and dried over magnesium sulfate and the solvent removed in vacuo to give the crude product, which was examined by \(^1\)H NMR. \(\delta_H (300\text{ MHz}; \text{CDCl}_3)\) 7.09 (1H, br s, N-H), 6.20 (2H, 2 s overlapping, ArH), 4.28 (4H, m, 2 × CH₂), 3.92 (9H, m, 3 × ArCH₃), 1.36 (6H, m, 2 × CH₃).

\(N-(2,4,6-\text{Trimethoxyphenyl})\text{hydrazinecarboxylic acid ethyl ester}\ 39.68,69\) (Microwave Irradiation)

\[
\begin{align*}
\text{OMe} & \quad \text{MeO} \\
\text{MeO} & \quad \text{OMe}
\end{align*}
\]

A mixture of 1,3,5-trimethoxy benzene 38 (16.80 mg, 0.1 mmol), DEAD (17.40 mg, 0.1 mmol) and freshly prepared InCl₃SiO₂ (50.40 mg) was transferred into a microwave tube and exposed to irradiation at 300 watts, 7 psi for 3 min at 100 °C. Since only reactants were present, the temperature was raised to 200 °C and the reaction re-run under the same conditions. The mixture turned black and 1H NMR showed no obvious products. Therefore, the reaction was re-commenced with fresh materials, using the following conditions: power: 300 watts; pressure: 7 psi; time: 5 min; temperature: 150 °C.

Two reactions were run using these conditions, one in THF and the other in 1,2-dichloroethane. The reaction proceeded well in THF but failed in 1,2-dichloroethane. \(\delta_H (300\text{ MHz}; \text{CDCl}_3)\) 6.40 (1H, br s, N-H), 6.01 (2H, s, 2 × ArH), 4.13 (4H, m, 2 × CH₂), 3.70 (9H, m, 3 × ArCH₃), 1.20 (6H, m, 2 × CH₃); Values slightly offset compared to previous data. All other data in agreement with literature values.68,69
2,4,6-Trimethoxyphenylamine 40

\[
\begin{align*}
\text{HN—C—OEt} & \quad \text{OMe} \\
\text{MeO} & \quad \text{HN—C—OEt} \\
C_{19}H_{22}N_2O_7 & \quad \text{C}_{18}H_{22}N_2O_7 \\
\text{Mol. Wt.: 342.34} & \quad \text{Mol. Wt.: 342.34}
\end{align*}
\]

To a solution of the newly obtained crude hydrazide 39 (0.50 g, 1.46 mmol) in glacial acetic acid (7.5 ml) under a nitrogen atmosphere, was added newly activated zinc dust (0.8 g, 12.33 mmol) portionwise over 5 min. The resulting mixture was stirred at room temperature overnight. The reaction was quenched by adding water and sodium hydroxide (10 M) to pH 10 and extracted with ethyl acetate. The organic layer was dried over magnesium sulfate and the solvent was removed under vacuum. The product was purified by Kugelkhor distillation, b.p. 113-116 °C /0.5 mmHg. All other data in agreement with literature values.

\[\text{A-(2-Methoxyphenyl)-hydrazinecarboxylic acid ethyl ester.}^{68,69}\]

\[
\begin{align*}
\text{HN—C—OEt} & \quad \text{OMe} \\
\text{MeO} & \quad \text{HN—C—OEt} \\
C_{13}H_{22}N_2O_7 & \quad \text{C}_{18}H_{22}N_2O_7 \\
\text{Mol. Wt.: 108.14} & \quad \text{Mol. Wt.: 282.29}
\end{align*}
\]

A mixture of methoxybenzene 41 (10.80 mg, 0.1 mmol), DEAD (17.40 mg, 0.1 mmol), the catalyst (50.4 mg) and THF (1 ml) was irradiated in a microwave over at 300 watts, pressure 7 psi for 8 min at 160 °C. The reaction mixture was diluted with water (20 ml) and extracted with dichloromethane (3 × 15 ml). The organic layers were combined and dried over magnesium sulfate and the solvent removed in vacuo to give the product as a white solid, 20.04 mg, 71%; mp 57-59 °C; all other data in agreement with literature values.\[68\]
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N-(2,4,6-Trimethoxyphenyl)hydrazine-1,2-dicarboxylic acid 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorodiester

\[ \text{C}_{27} \text{H}_{20} \text{F}_{26} \text{N}_2 \text{O}_7 \]
\[ \text{Md. Wt: 978.42} \]

To a solution of 1,3,5-methoxybenzene 38 (0.08 g, 4.8 mmol) in dry dichloromethane (10 ml) was added \(^{174}\) DEAD (0.12 g, 0.14 mmol) and zinc iodide (4 mg, 1.19 mmol). This mixture was stirred at room temperature for 2.5 h, and a 25% solution of ammonium acetate (15 ml) was added and the whole left stirring overnight. The aqueous layer was extracted with ethyl acetate (6 x 15 ml), the layers collected, dried over magnesium sulfate and evaporated. The crude product was dried under reduced pressure and examined by \(^1H\) NMR. No identifiable material was recovered.

**General method for cyclisation reactions of aldehydes with 3-butyn-1-ol**

To a 50 ml round bottom flask containing 3-butyn-1-ol (1 eq) dissolved in 20 ml of dry dichloromethane was added a solution of an aldehyde (1 eq), in \(~10\) ml of dry dichloromethane. This was stirred for 5 min under nitrogen before the addition of indium trichloride (1eq). Usually the mixture changed colour from colourless to yellow-brown. The reaction was left stirring at room temperature overnight. The mixture was quenched with distilled water (20 ml), the layers separated and the aqueous layer extracted with diethyl ether (3 x 20 ml), the organic layers collected, washed with water (3 x 20 ml) and dried over magnesium sulfate. The solvent removed in vacuo and the residue purified by flash column chromatography.

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4-Chloro-2-benzyl-5,6-dihydro-2H-pyran 104

Prepared according to the general procedure using phenylacetaldehyde 103 (3.42 g, 28.5 mmol), 3-butyn-1-ol (2.00 g, 28.5 mmol) and indium chloride (6.38 g, 28.5 mmol). 4-Chloro-6-phenyl-3,6-dihydro-2H-pyran 104 was isolated as a pale yellow oil (2.38 g, 40%). \( R_f \) 0.56 (hexane:ethyl acetate 5:1); Found [M+H]^+ 209.0737; \( C_{12}H_{15}OCl \) requires 209.0733; \( \nu_{\text{max/cm}^{-1}} \) (nujol) 2915, 2810, 1626 (C=C), 1598, 1314, 1020, 824, 684 (C-Cl); \( \delta \) (300 MHz; CDCl$_3$) 7.31-7.19 (5H, m, Ar), 5.75 (1H, d, J 0.81, ClC=CH), 4.29 (1H, m, OCHCH$_2$Ph), 4.00 (1H, m, CH$_2$CHHO), 3.65 (1H, ddd, J 14.3, 10.4, 4.0, CH$_2$CHHO), 2.92 (1H, dd J 13.6, 7.2, CH$_2$Ph), 2.71 (1H, dd J 13.6, 6.8, CH$_2$Ph), 2.40 (2H, m, CH$_2$CCl), \( \delta \) (75 MHz; CDCl$_3$) 137.9 (CCl), 130.6 (C$_{\text{quart in Ar}}$), 129.8, 128.8, 128.4 (5 x C(Ar)), 126.5 (CCl=CH), 76.2 (OCHCH$_2$), 66.3 (CH$_2$CH$_2$O), 41.5 (CH$_2$CH$_2$O), 33.2 (CH$_2$Ar); \( m/z \) (Cl) 209 [(M+H)$^+$, 8%], 173 [(M-Cl)$^+$, 43%], 155 [100%], 143 [81%], 132 [(M-Ph)$^+$, 8%], 117 [(M-CH$_2$Ph)$^+$, 57%].

4-Chloro-2-pentyl-5,6-dihydro-2H-pyran 166

Prepared according to the general procedure using hexanal 112 (0.50 g, 5 mmol), 3-butyn-1-ol (0.35 g, 5 mmol) and indium trichloride (1.10 g, 5 mmol). 4-Chloro-6-pentyl-3,6-dihydro-2H-pyran 166 was isolated as a pale yellow oil (0.76 g, 80%). \( R_f \) 0.51
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(hexane:ethyl acetate 6:1); Found [M+H]^+ 189.1027; C_{10}H_{17}OCl requires 189.1046;
\nu_{\text{max}}/\text{cm}^{-1} (nujol) 2960, 2852, 1654 (C=C), 1598, 1454, 1250, 1101, 978, 702 (C-Cl);
\delta_{\text{H}} (400 MHz; CDCl_3) 5.69 (1H, d, J 2.8, CIC=CH), 3.97 (1H, m, OCHCH_2), 3.94 (1H, m, CH_2CHHO), 3.60 (1H, ddd, J 15.3, 11.8, 5.9, CH_2CHHO), 2.46 (2H, m, CH_2CH_2O), 1.43 (2H, m, OCHCH_2CH_2), 1.26-1.20 (6H, m, 3 \times CH_2), 0.81 (3H, t, J 6.5);
\delta_C (100 MHz; CDCl_3) 130.8 (Cl), 127.0 (CIC=CH), 74.5 (OCHCH_2), 63.7 (CH_2CH_2O), 34.9 (OCHCH_2CH_2), 31.7 (CH_2CH_2O), 24.7, 22.5 (3 \times CH_2), 13.8 (CH_3). m/z Cl 191 [(M+H)^+, C_{10}H_{17}ClO, 6%], 189 [(M+H)^+, C_{10}H_{17}ClO, 19%], 169 [100%], 153 [(M-Cl)^+, 92%], 123 [68%], 117 [(M-CH_2CH_2CH_2CH_3)^+, 93%]

4-Chloro-2-cyclohexyl-5,6-dihydro-2H-pyran 109

\[
\begin{align*}
\text{108} & \quad \text{C}_7\text{H}_{12}\text{O} \quad \text{Mol. Wt.: 112.17} \\
1. \text{HOCH}_2\text{CH}=\text{C} & \quad \text{2. InCl}_3, \text{DCM} \\
\text{109} & \quad \text{C}_{10}\text{H}_{17}\text{ClO} \quad \text{Mol. Wt.: 200.70}
\end{align*}
\]

Prepared according to the general procedure using cyclohexanecarboxaldehyde 108 (0.37 g, 3 mmol), 3-butyn-1-ol (0.21 g, 3 mmol) and indium trichloride (0.66 g, 3 mmol). 4-Chloro-6-cyclohexyl-3,6-dihydro-2H-pyran 109 was isolated as a pale yellow oil (0.38 g, 63%). R_f 0.5 (hexane:ethyl acetate 7:1); Found [M+H]^+ 201.1034; C_{11}H_{17}OCl requires 201.1046;
\nu_{\text{max}}/\text{cm}^{-1} (nujol) 2931, 2854, 1596 (C=C), 1450, 1344, 1079, 732 (C-Cl);
\delta_{\text{H}} (300 MHz; CDCl_3) 5.80 (1H, d, J 1.9, CIC=CH), 4.00 (1H, m, CH_2CHHO), 3.89 (1H, br s, OCHCH=CCl), 3.66 (1H, ddd, J 15.0, 11.2, 3.9, CH_2CHHO), 2.1 (1H, m, CHHCH_2O), 2.13 (1H, d, J 16.8, CHHCH_2O), 1.28-1.15 (11H in cyclohexyl);
\delta_C (75 MHz, CDCl_3) 130.0 (Cl), 126.1 (CIC=CH), 79.1 (OCH), 64.4 (CH_2CH_2O), 42.8 (CH (cyclohexyl)), 35.0 (CH_2CH_2O), 29.1, 28.3, 26.8, 26.3 25.9 (5 \times CH_2 (cyclohexyl)); m/z (Cl) 201 [(M+H)^+, 6%], 181 [100%], 180 [18%], 165 [(M)^+, Cl, 10%], 117 [(M-C_6H_{11})^+, 8%].
4-Chloro-2-isopropyl-5,6-dihydro-2H-pyran 168

Prepared according to the general procedure using dimethylacetaldehyde 167 (0.29 g, 4 mmol), 3-butyn-1-ol (0.28 g, 4 mmol) and indium trichloride (0.88 g, 4 mmol). The desired compound 168 was obtained as a pale yellow oil (0.23 g, 26%). Rf 0.31 (hexane:ethyl acetate 10:1); Found [M+H]^+ 161.0723; C_{10}H_{16}O requires 161.0733; ν_{\text{max/cm}^{-1}} (nujol) 2969, 2867, 1684, 1650 (C=C), 1089, 982, 661 (C-Cl); δ_H (400 MHz; CDCl_3) 5.78 (1H, d, J 2.3, CCl=CH), 4.03 (1H, m, CH_2CHHO), 3.65 (1H, ddd, 11.4, 7.5, 4.2, CH_2CHHO), 2.11 (1H, d, 18.4 CHHCH_2O), 1.78 (2H, m, CH_3CHCH overlapping CHHCH_2O), 0.88 (6H, m, 2 × CH_3); δ_C (100 MHz; CDCl_3) 130.0 (C=C=CH), 125.4 (ClC=CH), 79.6 (OCH), 64.0 (CH_2CH_2O), 33.0 (CH_3CHCH_3), 32.4 (CH_2CH_2O), 17.9 (CH_3CHCH), 17.5 (CH_3CHCH_3); m/z (Cl) 163 [(M+H-C_8H_13O^{35}Cl)^+, 31%], 161 [(M+H-C_8H_13O^{37}Cl)^+, 100%], 143 [73%], 117 [(M-C_3H_7)^+, 14%], 125 [40%].

2-Diphenylmethyl-4-chloro-5,6-dihydro-2H-pyran 170

Prepared according to the general procedure using diphenylacetaldehyde 169 (0.59 g, 3 mmol), 3-butyn-1-ol (0.21 g, 3 mmol) and indium trichloride (0.66 g, 3 mmol). The desired compound 170 was obtained as a pale yellow oil (0.39 g, 46%). Rf 0.32 (hexane:ethyl acetate 10:1); Found [M+H]^+ 285.1054; C_{18}H_{17}OCl requires 285.1046; ν_{\text{max/cm}^{-1}} (nujol) 3060, 3027, 1653 (C=C), 1495, 700 (C-Cl); δ_H (400 MHz; CDCl_3) 7.32-
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7.30 (10H, m, 2 × Ph), 5.72 (1H, d, 2.8, CIC=CH), 4.88 (1H, m, OCH), 4.06 (2H, m, overlapping OCHCH and CH₂CHHO), 3.72 (1H, ddd, 11.5, 7.5, 5.8, CH₂CHHO), 2.5 (1H, m, CHHCH₂O), 2.19 (1H, d, J 16.1 CHHCH₂O); δc (100 MHz; CDCl₃) 141.4, 141.2 (2 × C₄ quat (Ar)), 129.7 (CCL), 128.5, 128.3, 126.8 (10 × C (Ar), 125.4 (CCL=CH), 76.8 (OCH), 64.1 (CH₂CH₂O), 56.2 (OCHCH), 32.8 (CH₂CH₂O); m/z (CI) 287 [(M+H-C₁₈H₁₇O³⁷Cl)⁺, 18%], 285 [(M+H-C₁₈H₁₇O³⁵Cl)⁺, 50%], 249 [(M-Cl)⁺, 50%], 231 [100%], 167 [96%], 117 [(M-C₁₃H₁₁)⁺, 24%]

4-Chloro-2-(1-ethylpropyl)-5,6-dihydro-2H-pyran 172

\[
\begin{align*}
\text{Et} & \quad \text{Et} \\
\text{171} & \quad \text{172}
\end{align*}
\]

Prepared according to the general procedure using diethylacetaldehyde 171 (0.30 g, 3 mmol), 3-butyln-1-ol (0.21 g, 3 mmol) and indium trichloride (0.66 g, 3 mmol). The desired compound 172 was obtained as a pale yellow oil (0.27 g, 48%). Rₜ 0.27 (hexane : ethyl acetate 10:1). Found [M+H]⁺ 189.1046; C₁₁H₁₀ClNO₃ requires 188.0968; νmax/cm⁻¹ (nujol) 2975, 2868, 1682 (C=C), 1572, 1465, 1251, 889, 771 (C-Cl); δH (400 MHz; CDCl₃) 5.71 (1H, d, J 4.0, CIC=CH), 4.09 (1H, br s, OCH), 3.98 (1H, m, CH₂CHHO), 3.61 (1H, ddd, J 14.4, 10.7, 3.6, CH₂CH₂O), 2.51 (1H, m, CHHCH₂O), 2.05 (1H, d, J 18.2, CHHCH₂O), 1.45-1.27 (5H, m, OCHCH₂Eₗt overlapping 2 × CH₂ in 2Et), 0.84 (6H, m, 2 × CH₃); δC (100 MHz; CDCl₃) 129.5 (CCL), 126.0 (CIC=CH), 76.5 (OCH), 64.2 (CH₂CH₂O), 46.1 (OCHCH₂Eₗt), 33.0 (CH₂CH₂O), 21.8, 21.4 (2 × CH₂(Et)), 12.0, 11.9 (2 × CH₃(Et)); m/z (CI) 191 [(M+H)⁺, C₁₀H₁₇O³⁷Cl, 28%], 189 [(M+H)⁺, C₁₀H₁₇O³⁵Cl, 91%], 171 [43%], 153 [(M-Cl)⁺, 100%], 117 [(M-CHEt)₂, 71%].
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4-Chloro-2-(4-nitrophenyl)-5,6-dihydro-2H-pyran 173

Prepared according to the general procedure using 4-nitrobenzaldehyde 105 (0.60 g, 4 mmol), 3-butyne-1-ol (0.28 g, 4 mmol) and indium trichloride (0.88 g, 4 mmol). No reaction was observed at room temperature, so it was left refluxing over a weekend. After purification, a pale yellow oil of 173 was obtained (0.40 g, 41%). Rf 0.31 (hexane:ethyl acetate 8:1); Found [M+H]^+ 240.0427; C_{11}H_{10}ClNO_{3} requires 240.0423; v_{max}/cm^{-1} (nujol) 3077, 2859, 1708, 1652 (C=O), 1525, 1344 (C-NO_2), 1255, 889, 754 (C-Cl); δ_1H (300 MHz; CDCl_3) 8.13 (2H, d, J 8.8, C(3')H, C(5)H), 7.45 (2H, d, J 8.5, C(2')H, C(6)H), 5.83 (1H, d, J 2.1, CIC=CH), 5.18 (1H, br s, OCH), 4.02 (1H, m, CH_2CHHO), 3.80 (1H, ddd, J 13.2, 9.1, 4.1, CH_2CHHO), 2.92 (1H, m, CH_2CHHO), 2.0 (1H, d, 16.9, CHHCH_2O); δ_C (75 MHz; CDCl_3), 141.6 (C(CI)), 131.6 (C(1')), 128.2 (C(3')H & C(5')H), 125.2 (CIC=CH), 124.2 (C(2')H & C(6')H), 123.8 (C(4')), 76.1 (OCH), 64.2 (CH_2CH_2O), 33.0 (CH_2CH_2O); v_{max}/cm^{-1} (nujol) 3446, 2859, 1525, 1344, 1124, 754, 701; m/z (Cl) 242 [(M+H)^+ C_{11}H_{10}^{37}ClNO_3, 34%], 240 [(M+H)^+ C_{11}H_{10}^{35}ClNO_3, 100%], 204 [(M-Cl)^+ 12%].

4-Chloro-2-(2-phenethyl)-5,6-dihydro-2H-pyran 175

Prepared according to the general procedure using 3-phenyl-propionaldehyde 174 (0.40 g, 3 mmol), 3-butyne-1-ol (0.21 g, 3 mmol) and indium trichloride (0.66 g, 3 mmol). The desired
compound 175 was obtained as a pale yellow oil (0.27 g, 41%). Rf 0.38 (hexane:ethyl acetate 10:1); Found [M+H]^+ 223.0889; C_{15}H_{15}OCl requires 222.0811; \nu_{max}/cm^{-1} (nujol) 3027, 2929, 1735, 1656 (C=C), 1344, 1116, 741 (C-Cl); \delta_{H} (400 MHz; CDCl_3) 7.31-7.19 (5H, m, Ar), 5.79 (1H, d, J 1.9, ClC=CH), 4.13 (1H, m, OCH), 4.07 (1H, m, CH_2CH=HO), 3.71 (1H, ddd, J 15.3, 11.3, 4.0, CH_2CH=HO), 2.75 (2H, m, CH_2CH_2O), 2.40 (1H, m, OCHCH\textsubscript{2}CH\textsubscript{2}Ph), 2.1 (1H, m, OCHCH\textsubscript{2}CH\textsubscript{2}Ph), 1.86 (2H, m, CH\textsubscript{2}CH\textsubscript{2}Ph); \delta_{C} (100 MHz; CDCl_3) 141.7 (CCI), 129.8 (C\textsubscript{Ar} in Ar), 128.3, 128.2, 126.8, (5 x C\textsubscript{Ar}), 125.8 (ClC=CH), 73.9 (OCH), 63.7 (CH_2CH_2O), 36.6 (OCHCH\textsubscript{2}CH\textsubscript{2}Ph), 33.0 (OCHCH\textsubscript{2}CH\textsubscript{2}Ph), 31.2 (CH_2CH_2O); m/z (Cl) 187 [(M-Cl)^+ 28%], 169 [6%], 159 [21%], 117 [(M-CH\textsubscript{2}CH\textsubscript{2}Ph)^+ 100%].

4-Bromo-2-pentyl-5,6-dihydro-2H-pyran 176

Prepared according to the general method for cyclisation reactions of aldehydes with 3-butyn-1-ol (0.35g, 5 mmol), hexanal 112 (0.50g, 5 mmol), but using indium tribromide (1.77 g, 5 mmol). The product was obtained as a pale yellow oil containing an inseparable mixture of 4-bromo-2-pentyl-5,6-dihydro-2H-pyran 176 and 4-chloro-2-pentyl-5,6-dihydro-2H-pyran 166 (0.59g, 51%) with the ratio of 3:1. Rf 0.54 (hexane:ethyl acetate 6:1); Found [M+H]^+ 233.0541; C_{19}H_{17}O\textsubscript{2}Br requires 232.0463; \nu_{max}/cm^{-1} (nujol) 2931, 2859, 1733, 1647 (C=C), 1459, 1249, 1103, 1037, 879 (C-Br and C-Cl); \delta_{H} (400 MHz; CDCl_3) 5.94 (1H, d, J 5.1, BrC=CH), 5.71 (1H, d, J 3.8, ClC=CH), 4.00 superimposed (2H, m, 2 \times OCHCH\textsubscript{2}), 3.93 superimposed (2H, m, 2 \times CH\textsubscript{2}CH=HO), 3.63 superimposed (2H, m, 2 \times CH\textsubscript{2}CH=HO), 2.70 superimposed (2H, m, 2 \times CH\textsubscript{2}CH\textsubscript{2}O), 2.23 (1H, d, J 21.8, (Br)CH\textsubscript{2}CH\textsubscript{2}O), 2.12 (1H, d, J 11.4, (Cl)CH\textsubscript{2}CH\textsubscript{2}O), 1.28 super-imposed (4H, m, 2 \times OCHCH\textsubscript{2}), 1.27 super-imposed (12H, m, 6 \times CH\textsubscript{2}), 0.84 super-imposed (6H, m, 2 \times CH\textsubscript{3}); \delta_{C} (100 MHz; CDCl_3) 131.3 (BrC=CH), 127.0 (ClC=CH), 118.6 (CBr), 104.3 (CCI), 75.8.
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((Br)OCH), 74.7 ((Cl)OCH), 64.2 ((Br)CH₂CH₂O), 63.7 ((Cl)CH₂CH₂O), 35.1, 34.9, 34.9, 34.8 superimposed (4C, 2 × CH₂CH₂O and 2 × CH₂), 31.7, 31.1, 25.9, 25.7, 22.7, 22.5 (6 × CH₂), 14.0 ((Br)CH₃), 13.9 ((Cl)CH₃); m/z (EI) 234 [(M)+ C₁₀H₁₇⁻¹BrO, 97%], 232 [(M)+, 12%], 231 [100%], 153 [(M-Br)+, 86%]

4-Bromo-2-cyclohexyl-5,6-dihydro-2H-pyran 110

Prepared according the general procedure using 3-butyn-1-ol (0.21 g, 3 mmol), cyclohexyl carboxyaldehyde 108 (0.34 g, 3 mmol) and indium tribromide (1.06 g, 3 mmol) to give an inseparable mixture of 4-Bromo-6-cyclohexyl-3,6-dihydro-2H-pyran 110 and 4-Chloro-6-cyclohexyl-3,6-dihydro-2H-pyran 109 (0.56 g of mixture, in the ratio of 2.5:1). Rf 0.50 (hexane:ethyl acetate 6:1); Found [M+H]^+ 245.0463; C₁₁H₁₇⁻¹BrO +H requires 244.0463; v max/cm⁻¹ (nujol) 2927, 2852, 1650 (C=C), 1450, 1340, 1253, 1081, 860, 759 and 734 (C-Br and C-Cl); δH (300 MHz; CDCl₃) 6.3 (1H, br s, BrC=CH), 5.80 (1H, br s, C1C=CH), 3.98 (2H, m, 2 × CH₂CH₂O), 3.87 (2H, m, 2 × OCH), 2.70 (1H, m, (Br)CHHCH₂O), 2.55 (1H, m, (Cl)CHHCH₂O), 2.26 (1H, d, J 16.1, (Br)CHHCH₂O), 2.18 (1H, d, J 14.1, (Cl)CHHCH₂O), 1.76-1.67, 1.23-1.07 super-imposed (22H, m, 2 × cyclohexyl); δC (75 MHz; CDCl₃) 130.4 (BrC=CH), 130.0 (ClC=CH), 119.3, 119.3 super-imposed (BrC), (ClC), 80.4 ((Br)OH), 79.4 ((Cl)OCH), 64.9 ((Br)CH₂CH₂), 64.4 ((Cl)CH₂CH₂), 42.9, 42.8 super-imposed (2 × OCHCHCH₂CH₂), 35.7 ((Br)CH₂CH₂O), 33.5 ((Cl)CH₂CH₂O), 28.9, 28.8, 28.5, 28.3, 28.3, 26.8, 26.7, 26.5, 26.4, 26.0 (10C, 2 × cyclohexyl); m/z (Cl) 247 [(M+H)^+, C₁₁H₁₈⁻¹BrO, 62%], 245 [(M+H)^+, C₁₁H₁₈⁻¹BrO, 73%], 203 [(M+H)^+, C₁₁H₁₇⁻¹ClO, 20%], 201 [(M+H)^+, C₁₁H₁₇⁻¹ClO, 65%], 165 [100%]
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4-Bromo-2-benzyl-5,6-dihydro-2H-pyran 111

Prepared according to the general procedure 3-butyn-1-ol (0.21 g, 3 mmol), phenylacetaldehyde 103 (0.36 g, 3 mmol) and indium tribromide (1.06g, 3 mmol) gave an inseparable mixture of 4-Bromo-6-phenyl-3,6-dihydro-2H-pyran 111 and 4-Chloro-6-phenyl-3,6-dihydro-2H-pyran 104 (0.4g, of mixture, in the ratio of 2.5:1). Rf 0.46 (hexane:ethyl acetate 8:1); Found [M+H]^+ 253.0228; C_{12}H_{14}BrO requires 252.0150; ν_{max}/cm^{-1} (nujol) 2922, 2853, 1643 (C=C), 1495, 1455, 1340, 1112, 1051, 906, 841 and 740 (C-Br and C-Cl); δ_{H} (300 MHz; CDCl_{3}) 7.31-7.20 super-imposed (10H, m, Ar), 6.00 (1H, d, J 5.04, BrC=CH), 5.77 (1H, d, J 1.05, ClC=CH), 4.30 super-imposed (2H, m, 2 × OCHCH_{2}Ph), 4.02 super-imposed (2H, m, 2 × CH_{2}CHHO), 2.93 super-imposed (2H, m, 2 × CHHPh), 2.72 super-imposed (2H, m, 2 × CH_{2}Ph), 2.66 (1H, m, (Br)CHHCH_{2}O), 2.58 (1H, m, (Cl)CHHCH_{2}O), 2.30 (1H, d, J 16.0, (Br)CHHCH_{2}O), 2.17 (1H, d J 11.2, (Cl)CHHCH_{2}O); δ_{C} (75 MHz; CDCl_{3}) 137.8, 137.7 super-imposed (BrC), (ClC), 130.7, 130.5, 129.7, 129.3, 128.8, 128.7 super-imposed (10 × C(Ar)), 126.9 (BrC=CH), 126.4 (ClC=CH), 119.8, 119.7 super-imposed (2 × C_{quart} in Ar), 77.1 ((Br)OCH), 76.1 ((Cl)OCH), 64.7 ((Br)CH_{2}CH_{2}O), 64.2 ((Cl)CH_{2}CH_{2}O), 41.8, 41.7 superimposed (2 × CH_{2}CH_{2}O), 35.4 ((Br)CH_{2}Ph), 33.3 ((Cl)CH_{2}Ph); m/z (Cl) 255 [(M+H)^+, C_{12}H_{13}^{79}BrO, 30%], 253 [(M+H)^+, C_{12}H_{13}^{79}BrO, 32%], 211 [(M+H)^+, C_{12}H_{13}^{37}ClO, 12%], 209 [(M+H)^+, C_{12}H_{13}^{35}ClO, 34%], 173 [61%], 155 [100%].
4-Bromo-2-pentyl-5,6-dihydro-2H-pyran 176

Prepared according to the general procedure and identical to the previous experiment, using 3-butyn-1-ol (0.21 g, 3 mmol), hexanale 112 (0.3 g, 3 mmol) and indium tribromide (1.06 g, 3 mmol) but employing CH\(_2\)Br\(_2\) as the reaction solvent, to give a pure sample of 4-bromo-2-pentyl-5,6-dihydro-2H-pyran 176 (0.49 g, 71%) as a pale yellow oil. R\(_f\) 0.46 (hexane:ethyl acetate 7:1); Found [M+H]\(^+\) 253.0531; C\(_{10}\)H\(_{17}\)BrO requires 232.0463; \(\nu_{\text{max}}/\text{cm}^{-1}\) (nujol) 2910, 2849, 1654 (C=C), 1460, 1312, 1100, 906, 840 (C-Br); \(\delta_{\text{H}}\) (300 MHz; CDCl\(_3\)) 5.93 (1H, d, \(J\) 5.0, BrC=CH), 3.90 (2H, m, overlapping OCHCH\(_2\) and CH\(_2\)CHO), 3.63 (1H, ddd, \(J\) 12.9, 9.8, 4.9, CH\(_2\)CHO), 2.40 (2H, m, CH\(_2\)CH\(_2\)O), 1.31-1.18 (8H, m, 4 \(\times\) CH\(_2\)), 0.82 (3H, t, \(J\) 5.1, CH\(_3\)); \(\delta_{\text{C}}\) (75 MHz; CDCl\(_3\)) 131.7 (BrC=CH), 119.1 (CBr), 76.2 (OCHCH\(_2\)), 64.7 (CH\(_2\)CH\(_2\)O), 33.5 (CH\(_2\)CH\(_2\)O), 32.2, 31.6, 25.2, 22.9 (4 \(\times\) CH\(_2\)), 14.4 (CH\(_3\)); \(m/z\) (Cl) 235 [(M\(^+\)], C\(_{10}\)H\(_17\)BrO, 19%], 233 [(M\(^+\)], C\(_{10}\)H\(_17\)BrO, 21%], 183 [(M\(^+\)], 16%], 171 [(M\(^+\)], 66%], 153 [(M\(^+\)], -Br, 100%.

4-Chloro-2-benzyltetrahydropyran 114

Prepared according to the general procedure using 4-phenylacetaldehyde 103 (0.36 g, 3 mmol), 3-buten-1-ol (0.15 g, 2 mmol) and indium trichloride (0.88 g, 4 mmol) in chloroform (20 ml). After was left stirring overnight and after purification a pale yellow oil
of 114 was obtained (0.36 g, 86%). Rf 0.52 (hexane:ethyl acetate 6:1); Found [M+H]^+ 211.0879; C_{12}H_{15}ClO requires 211.0889; m/z (Cl) 213 [(M)^+, C_{12}H_{15}^{37}ClO, 31%], 211 [(M)^+, C_{12}H_{15}^{35}ClO, 100%], 175 [(MH)^+, -Cl, 76%], 157 [(M)^+, 80%], 133 [(MH)^+, -Ph, 7%], 131 [(M)^+, 50%], 121 [(MH)^+, -CH_2Ph, 28%]; All other data were in agreement with previously reported values^152.

4-Chloro-2-pentyl-5,6-dihydro-2H-pyran 166

\[
\begin{align*}
\text{112} & \quad \text{Cl} \\
\text{C}_9\text{H}_{12}\text{O} & \quad \text{Mol. Wt.: 100.16} \\
\rightarrow & \quad \text{BF}_3\text{O(C}_2\text{H}_5)_2\text{DCM} \\
\text{166} & \quad \text{C}_{10}\text{H}_{15}\text{ClO} \\
& \quad \text{Mol. Wt.: 188.69}
\end{align*}
\]

Prepared according to the general procedure, but using boron trifluoride diethyl etherate as the Lewis acid. The title compound was prepared using 3-butyn-1-ol (0.21 g, 3 mmol), hexanal 112 (0.30 g, 3 mmol) and boron trifluoride diethyl etherate (0.43 g, 3 mmol) and was obtained as a pale yellow oil of 166 (0.37 g, 22%) Found [M+H]^+ 189.1046; C_{10}H_{17}^{35}ClO requires 189.1035; ν_{max}/cm^{-1} (nujol) 2960, 2852, 1727 (C=C), 1461, 1272, 1122, 1072, 742 (C-Cl); δH (400 MHz; CDCl_3) 5.73 (1H, d, J=4.8, ClC=CH), 4.11 (1H, br s, OCH), 4.01 (1H, m, CH_2CHHO), 3.62 (1H, ddd, J=14.4, 10.7, 3.7, CH_2CHHO), 2.58 (1H, m, CHHCH_2O), 2.10 (1H, d, J=16.4), 1.34-1.28 (8H, m, 4 × CH_2), 0.88 (3H, m, CH_3); δC (100 MHz; CDC_13) 132.4 (CCl), 130.8 (Cl=C=CH), 76.5 (OCHCH_2), 68.0 (CH_2CHHO), 33.0 (CH_2CH_2O), 30.3, 28.9, 23.7, 22.9 (4 × CH_2), 10.9 (CH_3); m/z Cl 191 [(M+H)^+, C_{10}H_{17}^{37}ClO, 32%], 189 [(M+H)^+, C_{10}H_{17}^{35}ClO, 100%], 153 [(M-Cl)^+, 88%], 119 [18%], 117 [(M-C_3H_11)^+, 60%].
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2-Pentyl-4-trifluoromethanesulfonyloxy-5,6-dihydro-2H-pyran 177

The title compound was prepared using 3-butyn-1-ol (0.21 g, 3 mmol), hexanal 112 (0.30 g, 3 mmol) and trimethylsilyl trifluoromethanesulfonate (0.80 g, 3 mmol) and was obtained as a pale yellow oil (0.47 g, 52%) with the ratio of 177 and 166 in a ratio of 2.1:1. Rf 0.26 (petroleum ether:ethyl acetate 16:1); Found [M+H]+ 303.0869; C11H17F3O4S + H requires 303.0878; νmax/cm⁻¹ (nujol) 2963, 2858, 1690 (C=C), 1416, 1349, 1206, 1143, 887, 761 (C-Cl) δH (400 MHz; CDCl3) 5.75 (1H, d, J 5.0, CIC=CH), 5.71 (1H, d, J 4.4, CF3SO2OC=CH), 4.18 superimposed (2H, m, 2 × OCH), 4.10-4.05 superimposed (2H, m, 2 × CH2CHHO), 3.71-3.65 (2H, m, 2 × CH2CHHO), 2.62 (1H, m, (CF3SO2OCCHHCH2O), 2.54 (1H, m, CICCHHCH2O), 2.23 (1H, d, J 12.2, CF3SO2OCCHHCH2O), 2.12 (1H, d J 14.0, CICCHHCH2O), 1.55-1.27 superimposed (16H, m, 2 × OCHCH2CH2CH2CH2CH3), 0.87 superimposed (6H, m, 2 × CH3); δC (100 MHz; CDCl3) 127.1 (CIC=CH), 120.6 (CF3SO2OC=CH), 74.8 ((Cl)OCH), 73.3 ((CF3SO2O)OCH), 63.8 (CICCH2CH2O), 63.2 (CF3SO2OCCHHCH2O), 35.0, 34.7, 31.6, 31.5 superimposed (4 × CH2), 28.8 (CICCH2CH2O), 28.3 (CF3SO2OCCH2CH2O), 24.7, 24.5, 22.5, 22.4 superimposed (4 × CH2), 13.99, 13.94 superimposed (2 × CH3); δF (376 MHz; CDCl3) 90.0 (3F, s, CF3); m/z (CI) 303 [15%], 231 [37%], 191 [(M+H)+ C10H1737ClO, 22%], 189 [(M+H)+ C10H1735ClO, 69%], 169 [28%], 153 [(M-SO2CF3)H]+, 100%, 123 [42%].
Butadiene monoepoxide 117 (1.40 g, 20 mmol) was cooled to 0°C and triethylamine trihydrofluoride (6.44 g, 40 mmol) added under a nitrogen atmosphere. Stirring was continued for a further 20 min at this temperature and then at 70 °C for 8 h. The mixture was diluted with water (20 ml) and extracted with diethyl ether (3 × 20 ml), the organic layers combined, washed with sodium hydrogencarbonate until the solution became basic, the layers then separated and the organic layer dried over magnesium sulfate. The excess of solvent was removed in vacuo and the title compound purified by distillation (60-62 °C at atmosphere pressure). The reaction was carried out several times, the best yield being (1.12g, 62%); ν max/cm⁻¹ (nujol) 3386 (-OH), 2924, 1424, 1050 (C-F), 850; δ H (400 MHz; CDCl₃) 5.87 (1H, m, CH₂CH), 5.46 (1H, dd, J 16.9, 3.0, CH₂CH₂), 5.34 (1H, d, J 10.7, CH₂CH₂), 5.06 (1H, m, JHF 49.2, CHF), 3.74 (2H, m, CHFCH₂), 2.04 (1H, s, OH); δ C (100 MHz; CDCl₃) 132.3 (CH₂CH), 119.1 (CH₂CH), 93.7 (d, J 167.8, CHF), 64.9 (CHFCH₂); δ F (376 MHz, CDCl₃) -24.5 (1F, m, CHF). The sample is too volatile to obtain mass spectrum.

General method for cyclisation reactions of aldehydes with fluorinated homoallylic alcohols

In a 50 ml round bottom flask containing the fluorinated homoallylic alcohol 118 (1 eq) dissolved in dry dichloromethane (10 ml) at room temperature was added an aldehyde (1.5 eq) and after five min, indium trichloride (2 eq). The mixture was left stirring for a further 20 min at room temperature and then heated to reflux for various lengths of time, as indicated by consumption of starting material title. After cooling to room temperature, water (20 ml) was added and the mixture extracted with diethyl ether (3 × 20 ml), the organic layers collected, dried over magnesium sulfate and the solvent removed in vacuo.
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The reaction mixture was then purified by flash column chromatography to afford the corresponding cyclisation product.

4-Chloro-5-fluoro-2-benzyltetrahydropyran 119

Prepared according to the general procedure using 2-fluorobut-3-en-1-ol 118 (0.20 g, 2.2 mmol), phenylacetaldehyde 103 (0.39 g, 3.3 mmol) and indium trichloride (0.98 g, 4.4 mmol) and heating for 2 h. 4-Chloro-5-fluoro-2-benzyltetrahydropyran 119 was isolated (0.35 g, 70%) as a colourless oil. Rf 0.29 (petroleum ether:ethyl acetate 25:1); Found [M+H]+ 229.0790; C12H14ClFO requires 229.0795; νmax/cm⁻¹ (nujol) 2933, 2850, 1652, 1448, 1118 (C-F), 910, 732, 701 (C-Cl); δH (400 MHz; CDCl3) 7.34-7.18 (5H, m, Ar), 4.58 (1H, dm, J 48.1, CHF), 4.24 (1H, m, CHeqH-O), 4.02 (1H, m, CHCl), 3.50 (2H, m, overlapping CHaxH-O and OCH), 3.01 (1H, dd, J 13.7, 6.7, CHHAr), 2.74 (1H, dd, J 13.7, 6.4, CHHAr), 2.01 (2H, m, C(Cl)CH₂); δC (100 MHz; CDCl3) 137.4 (C in benzene ring), 129.4, 128.49, 126.6 (5C, Ar), 87.1 (d, J 182.9, CHF), 78.1 (OCH), 69.0 (CH₂O), 56.1 (CHCl), 42.0 (CH₂Ar), 36.2 (ClCH₂); δF (376 MHz; CDCl₃) -35.3 (1F, m, CHF). m/z (Cl) 231 [(MH)+, C₁₂H₁₄ ClFO, 33%], 229 [(MH)+, C₁₂H₁₄ ClFO, 100%], 193 [(M-Cl)+, 10%], 163 [12%] 137 [(M-CH₂Ph)+, 26%].

4-Chloro-5-fluoro-2-pentyl-tetrahydropyran 178
Prepared according to the general procedure using 2-fluorobut-3-en-1-ol 118 (0.20 g, 2.2 mmol), hexanal 112 (0.33 g, 3.3 mmol) and indium trichloride (0.97 g, 4.4 mmol) in DCM (15 ml). The reaction was heated at reflux for 3.5 h and the target compound 178 was isolated as colourless oil. (0.07 g, 65%). Rf 0.18 (petroleum ether:ethyl acetate 22:1); Found [M+H]^+ 209.1065; C_{10}H_{18}ClFO requires 209.1108; ν max/cm⁻¹ (nujol) 2929, 2852, 1726, 1457, 1114 (C-F), 688 (C-Cl); δH (400 MHz; CDCl₃) 4.61 (1H, d, J = 56.1, CHF), 4.23 (1H, m, CH=C-H-O), 4.08 (1H, m, CHCl), 3.53 (2H, dd, J = 37.1, J = 36.9, CH=C-H-O), 3.33 (1H, m, O-CH₂), 2.02-1.97 (2H, m, CHClCH₂), 1.58-1.20 (8H, m, 4 x CH₂), 0.87 (3H, t, J = 6.7, CH₃); 1H NMR assignments were made by 1H-1H, 1H-13C and nOe experiments. δC (100 MHz; CDCl₃) 87.2 (d, J = 182.6, CHF), 77.1 (OCH), 68.9 (CH₂O), 56.3 (CHCl), 36.7 (CH₂), 35.5 (CH₂), 31.7 (CH₂), 24.9 (CH₂), 22.5 (CH₂), 14.0 (CH₃); δF (376 MHz; CDCl₃) -38.3 (1F, m, CHF); m/z (CI) 211 [(MH)^+, C_{10}H_{16}^{37}ClFO, 29%], 209 [(MH)^+, C_{10}H_{18}^{35}ClFO, 100%], 189 [(M-F)^+, 58%], 173 [(M-Cl)^+, 85%], 153 [25%], 135 [(M-C₅H₁₁)^+, 56%].

2-Diphenylmethyl-4-chloro-5-fluoro-tetrahydropyran 179

Prepared according to the general procedure using 2-fluorobut-3-en-1-ol 118 (0.15 g, 1.66 mmol), diphenylacetaldehyde 169 (0.49 g, 2.5 mmol) and indium trichloride (0.74 g, 3.32 mmol) in DCM (15 ml). After heating at reflux for 10 hrs the product 179 was observed in trace amounts by GCMS. Found [M+H]^+ 305.1111; C₁₈H₁₆ClFO requires 304.11108. m/z Cl 269 [(M-Cl)^+, 22%], 251 [100%].
4-Chloro-2-cyclohexyl-5-fluoro-tetrahydropyran 180

Prepared according to the general procedure using 2-fluorobut-3-en-1-ol 118 (0.15 g, 1.66 mmol), cyclohexylcarboxyaldehyde 108 (0.28 g, 2.5 mmol) and indium trichloride (0.74 g, 3.32 mmol) in DCM (15 ml). After heating at reflux for 4 h, 4-chloro-2-cyclohexyl-5-fluorotetrahydropyran 180 was isolated as a colourless oil (0.21 g, 61%). \( R_f 0.20 \) (petroleum ether:ethyl acetate 13:1); Found [M+H]\(^+\) 221.1186; \( C_{11}H_{18}ClFO \) requires 221.1108; \( \nu_{\text{max}}/\text{cm}^{-1} \) (nujol), 2927, 2852, 1652, 1558, 1120 (C-F), 690 (C-Cl), 647; \( \delta_H \) (400 MHz; \( \text{CDCl}_3 \)) 4.58 (1H, d, J 46.1, CHF), 4.23 (1H, m, CH$_{\text{cyclohexyl}}$-H-O), 4.02 (1H, m, CHCl), 2.48 (3H, m, overlapping CH$_{\text{cyclohexyl}}$H-O and CHCICH$_2$), 3.08 (1H, m, OCH), 2.01-1.44 (11H, m, cyclohexyl); \( \delta_C \) (400 MHz; \( \text{CDCl}_3 \)) 87.3 (d, J 182.5, CHF), 81.6 (OCH), 69.0 (CH$_2$O), 65.8 (CHCICH$_2$), 56.9 (CHCl), 42.4 (CH in cyclohexyl), 28.4 (2 x CH$_2$ in cyclohexyl), 26.2 (2 x CH$_2$ in cyclohexyl), 25.9 (CH$_2$ in cyclohexyl); \( m/z \) (Cl) 223 [(MH)$^+$, \( C_{11}H_{18}^{13}\text{ClFO} \), 31%], 221 [(MH)$^+$, \( C_{11}H_{18}^{35}\text{ClFO} \), 100%], 201 [(M-F)$^+$, 52%], 185 [(M-Cl)$^+$, 69%], 137 [(M-C$_6$H$_{11}$)$^+$, 18%].

2-Benzyl-5-fluoro-5,6-dihydro-2H-pyran 181

Prepared according to the general procedure using 2-fluorobut-3-en-1-ol 118 (0.15 g, 1.66 mmol), phenylacetaldehyde (0.30 g, 2.5 mmol) and trimethylsilyl trifluoromethanesulfonate.
(0.63 g, 3.32 mmol) in place of indium trichloride as Lewis acid. A colourless oil of 181 was isolated. (0.05 g, 56%). Rf 0.21 (petroleum ether:ethyl acetate 10:1). Found [M+H]$^+$ 193.1030; C$_{12}$H$_{13}$FO+H requires 192.0950; \( \nu_{\text{max}} \) cm$^{-1}$ (nujol), 3023, 2927, 1673 (C=C), 1496, 1375, 1097 (C-F), 955, 744; \( \delta \text{H} \) (400 MHz; CDCl$_3$) 7.16 (5H, m, Ar), 6.57 (1H, dd, J 85.4, CHF), 4.88 (4H, overlapping CHFHC=CH, CHFHC=CH and CH$_2$Ph), 3.73 (1H, m, OCH), 2.76 (1H, m, CHFCH=HO), 2.49 (1H, m, CHFCHO); [Here the shifts get a bit different from previous phenyl residue]. \( \delta \text{C} \) (100 MHz; CDCl$_3$) 148.9 (d, J 206.2, CHF), 133.1 (C$_\text{quart}$ in Ar), 126.4, 125.9, 124.2 (5 x C Ar), 106.6, 106.5 (2 x C (HC=CH)), 74.0 (OCH), 68.2 (CH$_2$Ph), 33.4 (CH$_2$O); \( \delta \text{F} \) (376 MHz; CDCl$_3$) -35.2 (1F, m, CHF); m/z (Cl) 193 [(MH)$^+$, C$_{12}$H$_{13}$FO, 75%], 175 [100%], 173 [68%], 145 [63%], 133 [98%], 105 [36%]

**5-Trimethylsilanylpent-4-yn-2-ol 157**

A solution of \(^n\)-butyllithium (2.5 M, 9.6 ml, 24 mmol) was added to a solution of 4-pentyn-2-ol (1.00 g, 12 mmol) in THF (30 ml) at \(-78^\circ\text{C}\) and the mixture stirred at this temperature for 2h. Then trimethylsilyl chloride (3.06 ml, 24 mmol) was added and the solution was allowed to warm to room temperature. During this time the colourless solution became cloudy white. At room temperature, dilute hydrochloric acid (20 ml) was added, the solution stirred for further 30 minutes and then extracted with diethyl ether (3 x 20 ml). The organic layer was washed with water, dried (MgSO$_4$) and concentrated. The desired compound 157 was obtained after distillation (70 °C, 0.5 mmHg) as a colourless oil. The reaction was repeated several times with the best yield (1.67 g, 89%). \( \delta \text{H} \) (300 MHz; CDCl$_3$) 3.78 (1H, m, CH$_2$CHCH$_2$), 2.23 (2H, m, CH$_2$CHCH$_2$), 2.03 (1H, br s, CHO$_2$H), 1.09 (3H, d, J 6.1, CH$_3$), 0.01 (9H, s, 3 x CH$_3$); All other data were in agreement with previously reported values.
5-Trimethylsilanylpent-4-en-2-ol 156\textsuperscript{149,150}

\[
\begin{array}{c}
\text{TMS} \quad \text{OH} \\
\text{157} \\
\text{C}_{2}\text{H}_{5}\text{OSi} \\
\text{Mol. Wt.: 158.2975}
\end{array}
\quad
\begin{array}{c}
\text{TMS} \quad \text{CH}_3 \\
\text{156} \\
\text{C}_{2}\text{H}_{5}\text{OSi} \\
\text{Mol. Wt.: 158.3133}
\end{array}
\]

A solution of 5-trimethylsilanylpent-4-yn-2-ol 157 (1.56 g, 10 mmol) in diethyl ether (100 ml) was cooled down to 0 °C and DIBAL (40 ml, 1 M solution in hexane, 40 mmol) was added slowly. After slowly warming to room temperature, the reaction was heated under reflux for 24 hours. After cooling to room temperature and then to 0 °C, diluted sulfuric acid (2 M, 50 ml) was added dropwise to the reaction mixture, which was stirred for a further 45 minutes whilst being allowed to warm to room temperature. The mixture was then filtered through celite, diluted with additional diethyl ether (200 ml) and water (100 ml) and the organic layer separated. The aqueous layer was extracted with diethyl ether (100 ml) and the organic layers combined, washed with cold water, dried (MgSO\textsubscript{4}) and concentrated in vacuo. Distillation gave a pale yellow oil of 156 (0.76 g, 49%; bp 121 °C/2mmHg).\textsuperscript{149,150} \[^{149,150}\]

\[^{149,150}\] The \[^{149,150}\] data were in agreement with previously reported values.

3-Benzylxypropan-1-ol 159

\[
\begin{array}{c}
\text{OH} \quad \text{OH} \\
\text{154} \\
\text{C}_{2}\text{H}_{6}\text{O}_2 \\
\text{Mol. Wt.: 78.0844}
\end{array}
\quad
\begin{array}{c}
\text{OH} \quad \text{O} \quad \text{Ph} \\
\text{159} \\
\text{C}_{10}\text{H}_{14}\text{O}_2 \\
\text{Mol. Wt.: 186.2170}
\end{array}
\]

Finely powdered potassium hydroxide (1.84 g, 33 mmol) was added to a solution of propane-1,3-diol 154 (4.8 ml, 66 mmol) in THF:DMSO (9:1, 120 ml) and after 5 minutes benzyl bromide (3.9 ml, 33 mmol) was added while the reaction mixture was kept at 0 °C...
(ice-bath). The mixture was stirred at room temperature for 24 hours. After this time water:diethyl ether (1:1, 250 ml) was added to the reaction mixture and the layers separated. The water layer was extracted with diethyl ether (2×200 ml) and ethyl acetate (2×200 ml), the organic layers were combined, dried (MgSO₄) and concentrated in vacuo. The residue was purified by column chromatography (petrol:diethyl ether = 1:1) to afford the title compound 159 as a colourless oil (5.72 g, 44%); Rf 0.18 (petrol:diethyl ether 1:1); ν_{max}/cm⁻¹ (neat) 3385 (OH), 2939 [Ar(C-H)], 1659 (C=C), 1485, 1460, 1367, 1198, 1081, 917, 748, 702; δ_H (300 MHz; CDCl₃) 7.13-7.25 (5H, m, Ar-H), 4.39 (2H, s, PhCH₂O), 3.62 (2H, m, OCH₂CH₂CH₂OH), 3.52 (2H, t, J 5.9, CH₂OCH₂Ph), 2.67 (1H, br s, OH), 1.73 (2H, m, OCH₂CH₂CH₂OH); δ_C (75 MHz; CDCl₃) 137.8 (C=O), 128.0 [2×C(Ar)], 125.7 [2×C(Ar)], 127.4 (C(Ar)), 72.9, 68.8, 61.1 and 32.1 (4×CH₂); m/z (Cl) 167 [(MH)+, 95%], 107 [(MH)+-C₃H₅O, 100%].

3-Benzylxypropionaldehyde 158

Dimethyl sulfoxide (1.1 ml, 16 mmol) was added to a solution of oxalyl chloride (0.7 ml, 8 mmol) in DCM (100 ml) at −78 °C. The reaction mixture was stirred for 10 minutes after which time 3-benzyloxypropan-1-ol 159 (1.20 g, 1 eq.) in DCM (5 ml) was added dropwise. After 15 minutes, triethylamine (5.1 ml, 36 mmol) was added, the solution stirred for 5 minutes, and then the reaction mixture warmed to room temperature. After stirring for 30 minutes the reaction was quenched with saturated ammonium chloride solution (15 ml), and the aqueous phase was washed with DCM (2×40 ml). The combined organic phase was washed with saturated NaHCO₃ (2×20 ml), brine (20 ml), dried (MgSO₄) and concentrated. Purification by flash chromatography (petrol:diethyl ether = 2:1) gave the title compound 158 as a clear oil (0.91 g, 77%); Rf 0.35 (petrol:diethyl ether 2:1); ν_{max}/cm⁻¹ (neat) 3032 [Ar(C-H)], 1726 (C=O), 1495, 1444, 1362, 1209, 1101, 906,
Chapter 6: Experimental

Levan Pivnevi

737, 691; δH (300 MHz; CDCl₃) 9.82 (1H, s, CHO), 7.28-7.41 (5H, m, Ar-H), 4.55 (2H, s, PhCH₂O), 3.84 (2H, t, J 6.1, CH₂OCH₂Ph), 2.72 (2H, t, J 6.1, OCH₂CH₂CHO); δC (75 MHz; CDCl₃) 200.9 (CHO), 137.6 (Cₜₜ), 128.2 [2xC(Ar)], 127.5 [2xC(Ar)], 127.4 (C(Ar)), 72.9, 63.5 and 43.6 (3xCH₂); m/z (Cl) 165 [(MH)⁺, 100%], 147 [(MH⁺-H₂O), 40%], 107 [(MH⁺-C₃H₈O), 95%].

(±)-Cis-2-(2-Benzylxyethyl)-6-methyl-5,6-dihydro-2H-pyran 153

![Chemical Structure](image)

The *title compound* was prepared according to the general procedure for the cyclisation, using 3-benzyloxy-1-propionaldehyde 158 (0.40 g, 2.4 mmol), indium trichloride (0.54 g, 2.4 mmol) and (±)-Z-5-trimethylsilylpent-4-en-2-ol 156 (0.39 g, 2.4 mmol), and isolated by flash chromatography (petrol:diethyl ether 5:1) as a colourless oil of 153 (0.54 g, 95%); Rf 0.25 (petrol:diethyl ether 5:1); Found [M+H]+ 233.1536; C₁₅H₂₁O₂+H requires 233.1541; νmax/cm⁻¹ (neat) 2852 (OCH), 1700 (C=C), 1449, 1357, 1209, 1178, 1157, 1086 (C-O), 896, 732, 691; δH (400 MHz; CDCl₃) 7.26-7.55 (5H, m, C(Ar)-H), 5.79 (1H, m, C(4)H), 5.64 (1H, dt, J 10.2, 1.9, C(3)H), 4.53 (2H, s, PhCH₂OCH₂), 4.31 (1H, m, C(2)H), 3.66 (3H, m, C(6)H, PhCH₂OCH₂), 1.95 (2H, m, C(5)H₂), 1.85 (2H, m, PhCH₂OCH₂CH₂), 1.22 (3H, d, J 6.2, C(6)CH₃); δC (100 MHz; CDCl₃) 138.7 (Cₜₜ), 130.2 (C(3)H), 128.3 [2xC(Ar)], 127.6 [2xC(Ar)], 127.4 (C(Ar)), 124.8 (C(4)H), 72.9 (PhCH₂O), 72.1 (C(2)H), 69.9 (C(6)H), 66.8 (CH₂CH₂OCH₂Ph), 35.7 (C₂H₃OCH₂CH₂), 32.9 (C(5)H₂), 21.7 (C(6)CH₃); m/z (Cl) 233 [(MH)⁺, 100%], 189 [(MH)+-C₂H₄O, 40%], 171 [(MH)+-C₂H₆O₂, 55%], 141 [(MH)+-C₇H₈, 60%].

---

146
(±)-Cis-6-(Methyltetrahydropyran-2-yl)acetic acid

\[
\begin{align*}
\text{Ph} & \quad \text{O} \\
\text{O} & \quad \text{O} \\
\text{153} & \\
\text{C}_{14} \text{H}_{14} \text{O}_2 & \quad \text{Mol. Wt.: 222.3181} \\
\text{H} & \quad \text{Pd/C} (10 \text{ mol } %), \text{EtOH} \\
\text{2} & \quad \text{CrO}_3/\text{H}_2\text{SO}_4/\text{H}_2\text{O} \\
\text{HO} & \quad \text{7} \\
\text{O} & \quad \text{2} \\
\text{C} & \quad \text{3} \\
\text{4} & \quad \text{5} \\
\text{6} & \\
\text{C}_6 \text{H}_{14} \text{O}_2 & \quad \text{Mol. Wt.: 158.1950}
\end{align*}
\]

2-(2-Benzylxyethyl)-6-methyl-5,6-dihydro-2H-pyran (0.40 g, 1.7 mmol) was dissolved in dry EtOH (4 ml) and Pd/C (0.04 g, 10 mol %) was added under a nitrogen atmosphere. The solution was then subjected to a hydrogen atmosphere by first flushing with hydrogen and then slowly bubbling hydrogen under the surface while the solution was vigorously stirred at room temperature. After being stirred under a hydrogen atmosphere overnight (19 h), the reaction mixture was filtered over celite and the solvent was removed \textit{in vacuo} to afford 6-(methyltetrahydropyran-2-yl)ethanol (0.24 g, 99%) which was used in the next step without further purification. 

\[
\begin{align*}
\delta_H (300 \text{ MHz; CDCl}_3) & \quad 3.81 (2H, m, \text{CH}_2\text{OH}), 3.57 (1H, m, \text{C(2 or 6)H}), 3.46 (1H, m, \text{C(2 or 6)H}), 3.10 (1H, br s, \text{OH}), 1.25-2.02 (8H, m, \text{C(3,4,5 and 7)H}_2), 1.14 (3H, d, J 6.2, \text{C(6)CH}_3).
\end{align*}
\]

6-(methyltetrahydropyran-2-yl)ethanol (0.24 g, 1.7 mmol) was dissolved in acetone (20 ml) at 0 °C and Jones reagent (12 ml) was added dropwise while the reaction mixture was vigorously stirred. [Preparation of the Jones reagent: concentrated sulfuric acid (1.5 ml, 27 mmol) was added dropwise with swirling to a solution of chromium trioxide (1.69 g, 17 mmol) in distilled water (24 ml) at 0 °C]. The reaction was warmed to room temperature and stirred for 3 h and followed by TLC. The mixture was poured into saturated brine (20 ml) and extracted with chloroform (5×20 ml). The combined organic phases were dried (MgSO\textsubscript{4}), filtered and the solvent was removed \textit{in vacuo} to give the crude oil that was purified by flash chromatography (DCM:diethyl ether = 3:1) to give the \textit{title compound} in the form of colourless crystals (0.07 g, 25%). All data are in the agreement with previously published literature values. 

\[
\begin{align*}
\text{Mp} & \quad 62-64 \degree \text{C (from DCM/diethyl ether); R} & \quad 0.33 (\text{DCM:diethyl ether 3:1); Found \ [M+H]^+ 159.1021; C_9\text{H}_{14}\text{O}_3+H \text{ requires 159.1021; } \nu_{\text{max/cm}^-1} (\text{KBr}) 3411 (\text{COOH}), 3098, 2934, 2868 (\text{OCH}), 1716 (\text{C=O}), 1434, 1367, 1301, 1203, 1060, 1029; \delta_H (400 \text{ MHz; CDCl}_3) 10.29 (1H, br s, \text{COOH}), 3.76 (1H, m, \text{C(2)H}), 3.50 (1H, m, \text{C(6)H}),
\end{align*}
\]

147
2.56 (1H, dd, J 15.6, 7.6, C(7)H₂), 2.46 (1H, dd, J 15.6, 5.2, C(7)H₂), 1.18-1.84 (6H, m, C(3, 4 and 5)H₂), 1.16 (3H, t, J 6.2, C(6)CH₃); δC (100 MHz; CDCl₃) 175.8 [Cquin(COOH)], 74.4 (C(6)H), 73.9 (C(2)H), 41.3 (C(7)H₂), 32.8, 30.8 and 23.2 (C(3-5)H₂), 21.9 (C(6)CH₃); m/z (CI) 159 [(MH)⁺, 100%], 141 [(MH)⁺-H₂O, 60%], 100 [(MH)⁺-C₃H₇O, 5%].

5-Benzylloxypentan-1-ol 164

\[
\begin{align*}
&\text{HO} \quad \text{CH} \\
&\text{165} \\
&\text{C}_2\text{H}_5\text{O}_2 \\
&\text{Mol. Wt.:} 104.15 \\
\end{align*}
\]

\[
\begin{align*}
&1. \text{BnBr} \\
&2. \text{KOH} \quad \text{THF-DMSO 9:1} \\
&\text{HO} \quad \text{O\text{Bn}} \\
&\text{164} \\
&\text{C}_2\text{H}_5\text{O}_2 \\
&\text{Mol. Wt.:} 194.27
\end{align*}
\]

Finely powdered potassium hydroxide (1.84 g, 33 mmol) was added to a solution of dried pentane-1,5-diol 165 (6.86 ml, 66 mmol) in THF:DMSO (9:1, 120 ml) at 0 °C and after 5 min benzyl bromide (5.64 g, 33 ml) was added, being careful to keep the temperature at 0 °C (ice-bath). The mixture was allowed to warm to room temperature and stirred for 24 h. After this time, water-diethyl ether (1:1, 250 ml) was added to the reaction mixture and the layers separated. The water layer was extracted with diethyl ether (2 x 200 ml) and ethyl acetate (2 x 200 ml), the organic layers combined, dried (MgSO₄) and concentrated in vacuo. The residue was purified by column chromatography Rf 0.2 (petrol:diethyl ether = 1:1) to afford the title compound 164 as an colourless oil (3.60 g, 28%); Found [M+H]⁺ 195.1384; C₁₂H₁₈O₂+H requires 195.1385; νmax/cm⁻¹ (nujol) 3386 (Bn), 2937, 2861, 1454, 1363, 1099, 736, 698; δH (300 MHz; CDCl₃) 7.28-7.20 (5H, m, Ar), 4.43 (2H, s, OCH₂Ph), 3.56 (2H, t, J 6.3, CH₂CH₂O), 3.41 (2H, t, J 6.4, HOCH₂), 1.47 (6H, m, 3 × CH₃); δC (75 MHz; CDCl₃) 138.9 (Cquart in Ar), 128.7, 128.0, 127.9 (5C in Ar), 73 (OCH₂Ph), 70 (CH₂CH₂O), 63 (HOCH₂), 32 (CH₂), 29 (CH₂), 22 (CH₂).
Dry dimethylsulfoxide (1.1 ml, 16 ml) was added to a solution of oxalyl chloride (1.02 g, 8 mmol) in dry DCM (100 ml) at -78 °C. The reaction mixture was stirred for 10 min after which time 5-benzyloxypentan-1-ol 164 (1.55 g, 8 mmol) in DCM (5 ml) was added dropwise. After 20 min, triethylamine (5.1 ml, 36 mmol) was added, the solution was stirred for 5 minutes and then allowed to warm to room temperature. After stirring for 30 min, the reaction was quenched with saturated ammonium chloride solution (15 ml) and the aqueous phase was washed with DCM (3 x 30 ml). The combined organic phase was washed with saturated NaHCO₃ (3 x 20 ml), brine (20 ml), dried (MgSO₄) and concentrated. Purification by flash chromatography (petrol:diethyl ether 2:1) gave the title compound 163 as a clear oil (1.04 g, 68%); Rf 0.36 (petrol:diethyl ether 2:1). Found [M+H]+ 193.1223; C₁₂H₁₆O₂+H requires 193.1228. v_max/cm⁻¹ (nujol) 2936, 2849, 1718 (CHO), 1457, 1361, 1100; δH (300 MHz; CDCl₃) 9.68 (1H, s, CHO), 7.30-7.22 (5H, m, Ar), 4.42 (2H, s, OCH3-Ar), 3.41 (2H, t, J 6.1, 5.9, OCH2CH2), 2.39 (2H, m, CH2CHO), 1.62 (4H, m, CH2CH2CH2CH2); δC (75 MHz; CDCl₃) 202.9 (CHO), 138.8 (C_quart in Ar), 128.8, 128.0, 127.9, (5C in Ar), 73.3 (ArCH2O), 70.1 (BnOCH2), 43.9 (CH2CHO), 29.5 (CH2), 19.3 (CH2); m/z (CI) 193 [(M)+, 34%], 133 [(M)+ ], 107 [(M)+-PhCH2O, 100%]

(±)-Clis-2-(4-Benzylxybutyl)-6-methyl-5,6-dihydro-2H-pyran 162
The aldehyde $163$ (0.57 g, 3 mmol) in DCM (20 ml) was added to a solution of the alcohol $156$ (0.32 g, 2 mmol) in 20 ml of DCM under atmosphere of nitrogen, stirred for 5 min and then indium chloride (0.88 g, 4 mmol) added. The resulting solution was left stirring overnight and then quenched with distilled water (20 ml). The layers were separated and the aqueous layer was extracted with diethyl ether (3 x 20 ml), the organic layers collected, washed with water (3 x 20 ml) and dried over magnesium sulfate. The solvent was removed in vacuo and the reaction mixture purified by flash column chromatography, giving the desired compound $162$ as pale yellow oil (1.00 g, 27%). $R_f$ 0.28 (hexane: diethyl ether 18:1); Found [M+H]$^+$ 261.1859; $C_{17}H_{24}O_2$ requires 261.1854; $\nu_{\text{max}}$/cm$^{-1}$ (nujol) 3029, 2933, 1463, 1363, 1099, 842; $\delta_H$ (400 MHz; CDCl$_3$) 7.34 (5H, m, Ar), 5.77 (1H, m, CH$_2$CH=CH), 5.61 (1H, m, CH$_2$CH=CHCH), 4.50 (2H, s, OCH$_2$Ph), 4.12 (1H, br s, OCH), 3.67 (1H, m, CH$_3$CHO), 3.48 (2H, m, CH$_2$OCH$_2$), 1.94 (2H, m, CH$_2$CH=CH), 1.66 (2H, m, CH$_2$CH$_2$O) 1.53 (4H, m, overlapping CHCH$_2$CH$_2$CH$_2$O), 1.21 (3H, d, J 6.24, CH$_3$); $\delta_C$ (100 MHz; CDCl$_3$) 138.6 (C$_{\text{quat}}$ in Ar), 130.1 (CH$_2$CH=CH), 128.5, 128.4, 127.6 (5C in Ar), 124.7 (CH$_2$CH=CH), 74.7 (OCH), 72.8 (OCH$_2$Ph), 70.3 (CH$_2$OCH$_2$), 69.9 (CH$_3$CHO), 35.4 (CH=CH-CH$_2$CH$_2$), 32.9 (CH$_2$CH=CH), 29.8 (CH$_2$CH$_2$O), 21.7 (overlapping CHCH$_2$CH$_2$CH$_2$O and CH$_3$); $m/z$ (Cl) 261 [(MH)$^+$, C$_{17}$H$_{24}$O$_2$, 100%], 225 [(MH)$^+$, 29%], 217 [49%], 169 [(M-CH$_2$Ph)$^+$, 100%], 153 [(MH-PhCH$_2$OH)$^+$, 73%], 135, 63%], 107 [(PhCH$_2$O)$^+$, 60%].

**(-)-cis-(6-Methyltetrahydropyran-2-yl)butanol 161**

![Chemical structure of 161](image)

(±)-cis-2-(4-Benzylxybutyl)-6-methyl-5,6-dihydro-2H-pyran $162$ (0.30 g, 1.15 mmol) was dissolved in dry ethanol (4 ml) and Pd/C (0.03g, 10 mol%) was added under a nitrogen atmosphere. The solution was then subjected to a hydrogen atmosphere by first flushing with hydrogen and then slowly bubbling hydrogen under the surface while the solution was vigorously stirred at room temperature. After being stirred under the atmosphere of
hydrogen overnight, the reaction mixture was filtered through celite and the solvent was removed in vacuo. The material was further purified by flash chromatography (ethyl acetate:petroleum ether 1:15) to afford 161 (0.14g, 71%). Rf 0.32 (ethyl acetate:petroleum ether 1:15); Found [M+H]^+ 173.1533; C_{10}H_{20}O_2 requires 173.1541; δH (400 MHz; CDCl_3) 3.64 (2H, t, J 6.3, CH_2OH), 3.40 (1H, m, CH_3CHO), 3.27 (1H, m, OCHCH_2), 1.80 (1H, br s, OH), 1.54 (12H, m, 6 × CH_2), 1.15 (3H, d, J 6.24, CH_3); δC (100 MHz; CDCl_3) 77.8 (OCHCH_2), 73.8 (CH_3CHO), 62.7 (CH_2OH), 36.0, 33.3, 32.6, 31.2, 23.7, 21.8 (6 × CH_2) 22 (CH_3); m/z (Cl) 173 [(MH)^+, C_{10}H_{20}O_2, 45%], 155 [(MH-H_2O)^+, 100%], 137 [52%], 111 [80%].

**Attempted Cyclisation 160**

To a solution of freshly crystallized 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (0.28g, 0.57 mmol) in anhydrous dichloromethane (5 ml) at -78 °C was added (±)-cis-(6-methyltetrahydropyran-2-yl)butanol 161 (0.10 g, 0.58 mmol). The mixture was allowed to reach room temperature over a period of 12h. It was filtered through a small amount of silica gel, which was subsequently washed with dichloromethane (200 ml). The combined filtrates were concentrated in vacuo and the residue was subject to flash chromatography (ethyl acetate:petroleum ether 1.33:1) to give only unidentified material.
REFERENCES

Chapter 7: References

25. Fluorous Technologies, Inc. www.fluorous.com
58. Adopted from the Open University Chem 777 residential school procedure.
Chapter 7: References


Appendix 1
Appendix 1

X-Ray data and $^1$H and $^{13}$C NMR data for (±)-c/s-6-(methyltetrahydroxypropyl-2yl)acetic acid

Table 1. Crystal data and structure refinement.

<table>
<thead>
<tr>
<th>Identification code</th>
<th>03sre0173</th>
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<tbody>
<tr>
<td>Empirical formula</td>
<td>C$<em>8$H$</em>{14}$O$_3$</td>
</tr>
<tr>
<td>Formula weight</td>
<td>158.19</td>
</tr>
<tr>
<td>Temperature</td>
<td>120(2) K</td>
</tr>
<tr>
<td>Wavelength</td>
<td>0.71073 Å</td>
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<tr>
<td>Crystal system</td>
<td>Triclinic</td>
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<tr>
<td>Space group</td>
<td>P-1</td>
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<tr>
<td>Unit cell dimensions</td>
<td>(a = 6.8220(2) \text{ Å} ) (\alpha = 64.2870(10)^\circ)</td>
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<tr>
<td></td>
<td>(b = 8.2332(2) \text{ Å} ) (\beta = 75.3220(10)^\circ)</td>
</tr>
<tr>
<td></td>
<td>(c = 8.7991(3) \text{ Å} ) (\gamma = 77.259(2)^\circ)</td>
</tr>
<tr>
<td>Volume</td>
<td>427.27(2) Å$^3$</td>
</tr>
<tr>
<td>Z</td>
<td>2</td>
</tr>
<tr>
<td>Density (calculated)</td>
<td>1.230 Mg / m$^3$</td>
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<tr>
<td>Absorption coefficient</td>
<td>0.093 mm$^{-1}$</td>
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<tr>
<td>(F(000))</td>
<td>172</td>
</tr>
<tr>
<td>Crystal size</td>
<td>Plate; colourless</td>
</tr>
<tr>
<td>(\theta) range for data collection</td>
<td>2.95 – 27.49$^\circ$</td>
</tr>
<tr>
<td>Reflections collected</td>
<td>9009</td>
</tr>
<tr>
<td>Independent reflections</td>
<td>1944 [(R_{int} = 0.0423)]</td>
</tr>
<tr>
<td>Completeness to (\theta = 27.49^\circ)</td>
<td>98.9 %</td>
</tr>
<tr>
<td>Absorption correction</td>
<td>Semi-empirical from equivalents</td>
</tr>
<tr>
<td>Max. and min. transmission</td>
<td>0.9981 and 0.9871</td>
</tr>
<tr>
<td>Refinement method</td>
<td>Full-matrix least-squares on (F^2)</td>
</tr>
<tr>
<td>Data / restraints / parameters</td>
<td>1944 / 0 / 103</td>
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<tr>
<td>Goodness-of-fit on (F^2)</td>
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</tr>
<tr>
<td>Final (R) indices ([R &gt; 2\sigma(F^2)])</td>
<td>(R1 = 0.0376, wR2 = 0.1047)</td>
</tr>
<tr>
<td>(R) indices (all data)</td>
<td>(R1 = 0.0452, wR2 = 0.1115)</td>
</tr>
<tr>
<td>Extinction coefficient</td>
<td>0.16(4)</td>
</tr>
<tr>
<td>Largest diff. peak and hole</td>
<td>0.282 and –0.209 e Å$^{-3}$</td>
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Special details:
Table 2. Atomic coordinates \( \times 10^4 \), equivalent isotropic displacement parameters \( \AA^2 \times 10^3 \) and site occupancy factors. \( U_{eq} \) is defined as one third of the trace of the orthogonalized \( \mathbf{U} \) tensor.

<table>
<thead>
<tr>
<th>Atom</th>
<th>( x )</th>
<th>( y )</th>
<th>( z )</th>
<th>( U_{eq} )</th>
<th>S.o.f.</th>
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Table 3. Bond lengths [Å] and angles [°].

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<th>Length/Angle</th>
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<tr>
<td>C1-C3</td>
<td>1.5259(15)</td>
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<tr>
<td>C2-H2B</td>
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</tr>
<tr>
<td>C2-H2C</td>
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</tr>
<tr>
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</tr>
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<td>H2B-C2-H2C</td>
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<td>Bond</td>
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Symmetry transformations used to generate equivalent atoms:
Table 4. Anisotropic displacement parameters \([\text{Å}^2 \times 10^3]\). The anisotropic displacement factor exponent takes the form: 

\[ -2\pi^2 [h^2 a^* U_{11} + \ldots + 2 h k a^* b^* U_{12} ] \].

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<th>$U_{12}$</th>
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$^{13}$C NMR