

Synthesis and Application of Fluorous-Tagged Phosphonium Salts.

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M.Phil

At the University of Leicester

By

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Statement of Originality

The experimental work in this thesis has been carried out by the author in the Department of Chemistry at The University of Leicester between September 2002 and July 2005. The work has not been submitted, and is not presently being submitted, for any other degree at this or any other University.

Signed.....*K. Weber*.....

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Synthesis and Applications of Fluorous-Tagged Phase Transfer Catalysts

Kathleen M. Weber

Abstract

This thesis details the synthesis of a range of fluorous-tagged phosphonium salts in order to investigate their applications as phase transfer catalysts (PTC). Fluorous-tagged phosphonium salts have been prepared by the quaternisation of the fluorous tertiary phosphines, $P(CH_2CH_2C_6F_{13})_3$, $P(4-C_6H_4C_6F_{13})_3$ and $P(4-C_6H_4CH_2CH_2C_8F_{17})_3$, with benzyl bromide (BnBr), butyl bromide (BuBr), 1*H*,1*H*,2*H*,2*H*-perfluorooctyl triflate ($C_6F_{13}CH_2CH_2OSO_2CF_3$) and butyl triflate ($n-C_4H_9OSOCF_3$) in clean and high yielding reactions.

All of the fluorous phosphonium salts were evaluated in potassium picrate extraction experiments in order to define their abilities to transfer picrate from an aqueous phase into an organic phase (benzotrifluoride). All of the salts showed good extraction of the picrate anion into the organic phase (68-100%) demonstrating their potential for phase transfer catalysis.

The fluorous-tagged phosphonium salts were tested in a model halide exchange reaction under phase transfer conditions. Both liquid-liquid and solid-liquid systems were tested, but the phosphonium salts performed better under liquid-liquid conditions. Recovery of the fluorous-tagged salts for subsequent reactions was attempted using fluorous reverse phase silica gel (FRPSG). Limited success was achieved due to the decomposition of the aromatic phosphonium salts during the phase transfer catalysed reaction.

The stability of the 1st generation of aromatic phosphonium salts was therefore examined under liquid-liquid (BTF/water) and solid-liquid (KI/BTF) phase transfer conditions. It was determined that the decomposition gave mainly the phosphine oxide and the stability of the phosphonium salts, that contained fluorous ponytails directly attached to the aromatic ring, was restricted under these conditions. A series of 2nd generation salts containing the $P(4-C_6H_4CH_2CH_2C_8F_{17})_3$ unit were synthesised and showed good preliminary stability results under liquid-liquid phase transfer conditions.

Acknowledgements.

Success is counted sweetest by those who ne'er succeeded.

Emily Dickinson, 1830 – 1886.

I would first like to dedicate my work in loving memory to my Uncle, David Francis Hunt, who was taken from our family so incredibly suddenly on 1st February 2006. I am sure that had he been alive today he would certainly have been incredibly proud of my work and my achievements, I only wish I could have shared this with him.

My deepest and most sincere thanks to my family, Iris, John and James Weber for their constant support and love throughout my research and whom kept me going despite the hard times, of which there were countless.

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List of Abbreviations

AIBN	2,2'-azobis(isobutyronitrile)
aq.	Aqueous
BTF	Benzotrifluoride
d	Doublets
dd	Doublet of doublets
DEAD	Diethylazodicarboxylate
DCM	Dichloromethane
DME	Dimethoxyethane
DMF	<i>N,N'</i> -dimethylformamide
DMSO	Dimethylsulfoxide
dt	Doublet of triplets
ES	Electro Spray
FAB	Fast atom bombardment
FMS	Fluorous mixture synthesis
F-HPLC	Fluorous high pressure liquid chromatography
FRP	Fluorous reverse phase
FRPSG	Fluorous reverse phase silica gel
GC	Gas chromatography
h	Hours
Hz	Hertz
HPLC	High pressure liquid chromatography
J	Coupling constant

m	Multiplet
Me	Methyl
MeOH	Methanol
m pt	Melting point
NBS	N-bromosuccinimide
NMR	Nuclear magnetic resonance
PFMC	Perfluoromethylcyclohexane
PFOB	Perfluorooctyl bromide
Ph	Phenyl
PH ₃	Phosphine
PP3	Perfluoro-1, 3-dimethylcyclohexane
PTC	Phase transfer catalysis
s	Singlet
SPE	Solid phase extraction
t	Triplet
TBAF	Tetrabutylammonium fluoride
td	Triplet of doublets
TEA	Triethylamine
TEMPO	2,2,6,6-tetramethyl-1-piperdinyloxy free radical
OTf	Triflate
THF	Tetrahydrofuran
TMAF	Tetramethylammonium fluoride
VAZO	1,1'-azobis(cyclohexanecarbonitrile)

Chapter One

1.1 Fluorous Biphasic Catalysis

In 1994 Horváth and Rábai introduced the concept of the fluorous biphasic system in order to simplify the separation of a homogenous catalyst from organic products.^{1,2} The system is derived directly from the aqueous biphasic system where the aqueous phase is replaced with a perfluorocarbon solvent, often called the fluorous phase, and relies on the immiscibility of organic and perfluorocarbon solvents. In order to render the catalyst preferentially soluble in the perfluorocarbon solvent, long perfluoroalkyl chains are directly attached to the active site, thereby increasing the solubility of the catalyst and anchoring it in to the fluorous phase. The organic substrates, which have no affinity for the perfluorocarbon phase, remain in the organic phase. Upon heating, both layers become miscible thereby forming a homogenous or monophasic system (Figure 1) that allows the organic substrate and catalyst to react. On cooling, the phases separate enabling easy and efficient separation of the catalyst from the organic products.

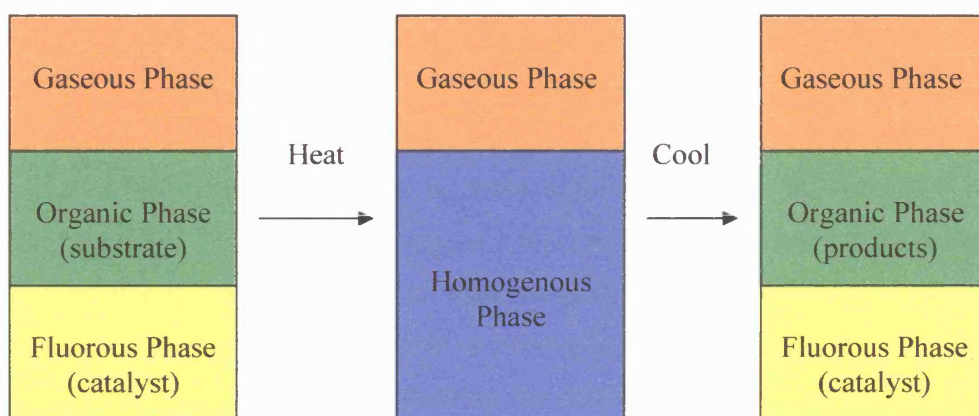


Figure 1 Fluorous Biphasic Catalysis.

Figure 2 shows the trialkylphosphine which was originally designed and synthesised by Horváth and Rábai. It contains three long perfluoroalkyl groups, often nicknamed fluorous ponytails, which render the phosphine preferentially soluble in the perfluorocarbon solvent. It is also important to observe the C_2H_4 spacer group which is used to insulate the phosphorus donor atom from the electron withdrawing effect of the

fluorous ponytails. Recently, Gladysz synthesised a series of trialkylphosphines whose spacer units vary from two to five methylene units.^{3,4} Studies were carried out into the efficiency of the spacer units by examining the stretching frequencies of the carbonyl bond in the *trans*-[IrCl(CO)L₂] complex, where L is the phosphine ligand to be tested.⁵ The data illustrated that even with five spacer units, the electron withdrawing inductive effects of the fluorous ponytails were still apparent. It has since been suggested that seven to eight methylene groups are required for complete insulation of the active site from the perfluoroalkyl section.⁶

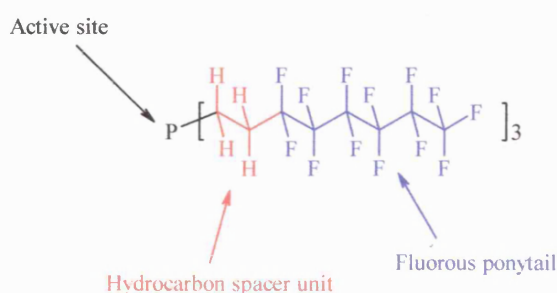


Figure 2 Trialkylphosphine.

A minimum of 60% fluorine content by mass within a molecule is required to provide preferential solubility of the fluorous tagged molecules in the perfluorocarbon phase.^{7,8} To achieve high fluorine content additional fluorous ponytails can be attached, however, this can cause an increase in molecular weight and cost which can be a limiting factor. Partition coefficients are important for understanding the characteristics of a fluorous compound when partitioned between a perfluorocarbon solvent and an organic solvent. The information obtained allows the optimization and design of a fluorous catalyst and reagent for a specific reaction. Gladysz *et al.* have investigated a wide range of trialkyl phosphines and determined partition coefficients experimentally^{3,4,8} with several trends apparent in Table 1. Firstly, as the length of the fluorous ponytails increase, the partition coefficients increase as expected. However, there is one drawback and that is the absolute solubility of the fluorous compounds normally decreases as the length of the perfluoroalkyl groups increase. Secondly, as the length of the hydrocarbon spacer group increases, the partitioning of the phosphine into the fluorous phase decreases (Table 1). Similar trends are

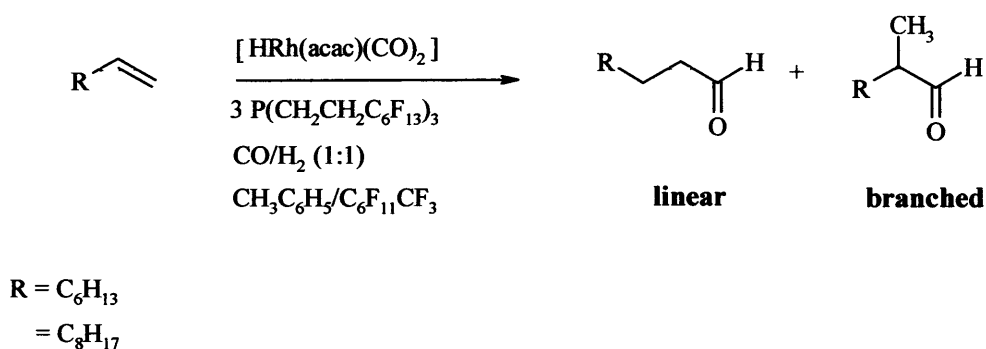
also seen for triarylphosphines; though the trialkylphosphines have better solubility in the perfluorocarbon phase compared to the triarylphosphines.

Phosphine	Solvent System	Partition (%) organic:fluorous	Percentage Fluorine (%)
$(\text{CF}_3(\text{CF}_2)_5\text{C}_2\text{H}_4)_3\text{P}$	$\text{CH}_3\text{C}_6\text{H}_5:\text{CF}_3\text{C}_6\text{F}_{11}$	1.2:98.9	69.1
$(\text{CF}_3(\text{CF}_2)_7\text{C}_2\text{H}_4)_3\text{P}$	$\text{CH}_3\text{C}_6\text{H}_5:\text{CF}_3\text{C}_6\text{F}_{11}$	<0.3:>99.7	70.6
$(\text{CF}_3(\text{CF}_2)_9\text{C}_2\text{H}_4)_3\text{P}$	$\text{CH}_3\text{C}_6\text{H}_5:\text{CF}_3\text{C}_6\text{F}_{11}$	<0.3:>99.7	71.6
$(\text{CF}_3(\text{CF}_2)_7\text{C}_3\text{H}_6)_3\text{P}$	$\text{CH}_3\text{C}_6\text{H}_5:\text{CF}_3\text{C}_6\text{F}_{11}$	1.2:98.8	68.5
$(\text{CF}_3(\text{CF}_2)_7\text{C}_4\text{H}_8)_3\text{P}$	$\text{CH}_3\text{C}_6\text{H}_5:\text{CF}_3\text{C}_6\text{F}_{11}$	1.1:98.9	66.5
$(\text{CF}_3(\text{CF}_2)_7\text{C}_5\text{H}_{10})_3\text{P}$	$\text{CH}_3\text{C}_6\text{H}_5:\text{CF}_3\text{C}_6\text{F}_{11}$	1.1:98.9	64.5

Table 1 Partition coefficients for a series of trialkylphosphines

In recent years the concept of the fluorous biphasic system has grown rapidly and a variety of catalytic reactions involving perfluoroalkyl derivatised ligands have been investigated and studied. Although most of the work has concentrated on phosphorus (III) ligands,^{9,10} many different ligand systems such as β -diketonates,¹¹ cyclopentadienides,¹² porphyrins,^{13,14} bipyridines,¹⁵ tetraazacyclotetradecanes^{16,17} and amino ligands¹⁸ have been functionalised with fluorous ponytails.

The hydroformylation of 1-decene and 1-octene (Scheme 1) was carried out using the catalyst, $[\text{HRh}(\text{CO})\{\text{P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3\}_3]$, under 10 bar of *syn* gas (carbon monoxide and hydrogen mix (1:1)) at 100 °C in toluene and perfluoromethylcyclohexane (PFMC).¹ On completion, the reaction mixture was cooled to room temperature in order to allow the phases to separate. Gas chromatography (GC) analysis of the organic phase indicated that there was high conversion to the aldehyde products (85 %) and a linear/branched ratio of 2.9. The lower fluorous phase was reused without loss of catalytic activity suggesting that there was no sign of catalyst leaching from the fluorous phase to the hydrocarbon phase.



Scheme 1 Hydroformylation of 1-octene and 1-decene.

A more detailed kinetic study of the hydroformylation of ethylene and 1-decene with the same fluorinated rhodium catalyst (generated *in situ*) was carried out and compared to the conventional Rh/PPh₃ system.¹⁹ The activity of the fluorinated catalyst was an order of magnitude lower than the standard Rh/PPh₃ catalyst. However, the fluorinated catalyst was continuously used over nine consecutive hydroformylations of decylene and showed minimal leaching of rhodium (1.18 ppm of Rh/mol of undecanals). All of this evidence suggested that the long term stability of the fluorinated rhodium catalyst was greater than the Rh/PPh₃ system.

In general, triarylphosphines give better linear selectivity in rhodium catalysed hydroformylation reactions than trialkylphosphines. At the University of Leicester work has been carried out on triarylphosphines and triarylphosphites which contain fluorinated ponytails (Figure 3).²⁰ Good selectivities and separation were obtained in the hydroformylation of 1-octene using these ligands in a monophasic system using perfluoromethylcyclohexane (PP2) as the solvent. 1-Octene is miscible in fluorinated solvents at >60 °C and under 20 bar CO/H₂ (1:1) whereas the high polarity of the aldehyde means that it is immiscible with the perfluorocarbon solvent and recovery can be obtained by simple separation. Good selectivity to the linear aldehyde (81 %) and good initial rates (8.5 mol dm⁻³ h⁻¹) were obtained at 70 °C under 20 bar CO/H₂. Rhodium leaching into the aldehyde phase was minimal at 0.05 % [0.08 mg Rh (mol aldehyde)⁻¹] of the rhodium charged and the phosphorus leaching was 3.3 %.

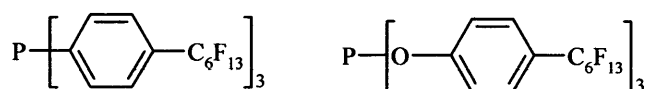
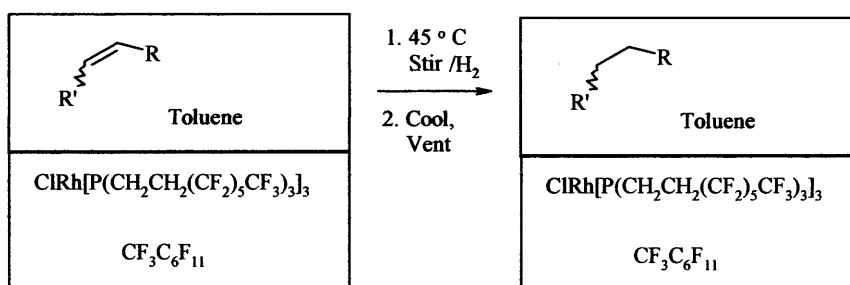


Figure 3 Triarylphosphine and triarylphosphite ligands

Hydroformylation reactions have also been carried out under supercritical carbon dioxide (scCO₂) conditions and have given substantially better rates of reactions using P(4-C₆H₄C₂H₄C₆F₁₃)₃. ScCO₂ is an excellent alternative solvent because of the environmental benefits for homogenous catalysis in which removal of the solvent is carried out by simple decompression back to its gaseous phase.²¹

Using the trialkylphosphine, P(CH₂CH₂C₆F₁₃)₃, Horváth *et al.* investigated the hydrogenation of alkenes (Scheme 2) using Wilkinson's Catalyst, [RhClL₃].²² A range of substrates such as 1-dodecene, 4-bromostyrene and cyclododecene were investigated using the fluoruous biphasic system. All substrates were successfully converted to the corresponding alkanes in greater than 85% yields. As before, recycling of the catalyst was carried out, but rates were greatly decreased unless the catalyst was transferred to a new tube in which case hydrogenations were found to proceed as normal.



Scheme 2 Fluorous biphasic rhodium – catalyzed alkene hydrogenation.

Selective oxidation reactions catalysed by transition metal complexes using stoichiometric amounts of either inorganic oxidants such as chromium (VI) salts or organic oxidants such as activated DMSO, have been studied for many years. However, the use of heavy metals and their impact on the environment are cause for concern. One area that has been extensively studied in the fluoruous biphasic system is the epoxidation of alkenes. Pozzi *et al.*, have prepared several polyfluorinated tetraphenylporphyrins (F-TPP, Figure 4) and demonstrated their catalytic applications for the epoxidation of alkenes with molecular oxygen under fluoruous biphasic conditions.¹³ More recently, the synthesis of a

perfluorinated triazamacrocyclic bearing three fluorine substituents was developed. These catalysts have been used in the oxidation of cyclohexene to 2-cyclohexen-1-one and 2-cyclohex-1-ol with good success.²³ Tetraazamacrocycles (Figure 5) have also been used as a pre-catalyst for metal complexes, such as metal carboxylates, to ensure complete solubility in the perfluorocarbon phase.¹⁷

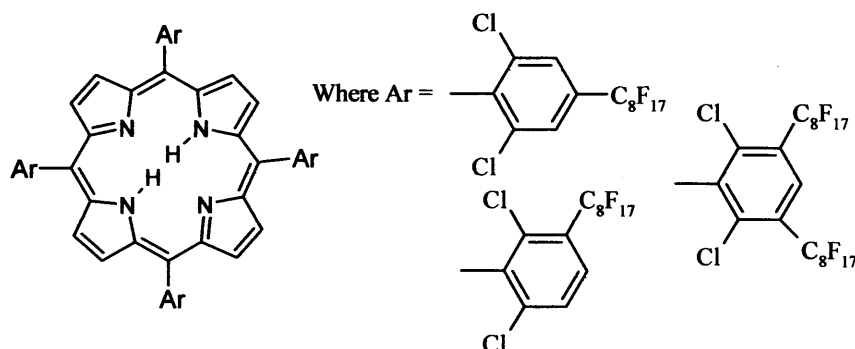


Figure 4 Fluorine tagged tetraphenylporphyrins

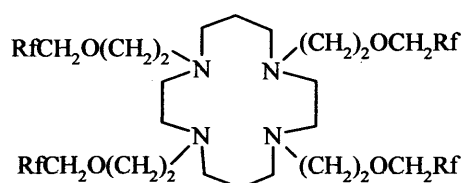
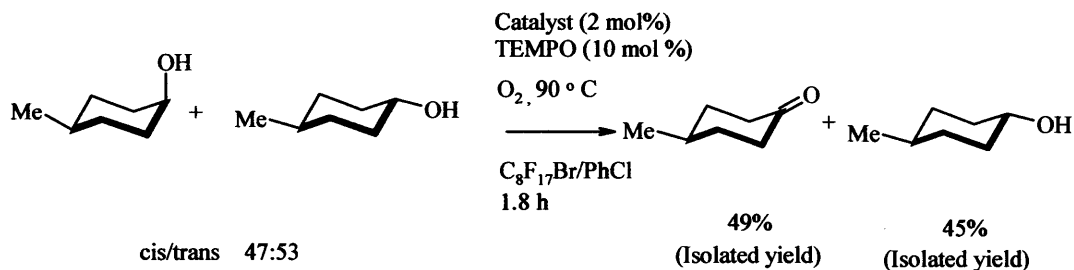


Figure 5 Fluorine tagged polyazamacrocyclics

Using fluorine biphasic catalysis Knochel *et al.* have demonstrated the aerobic oxidation of sterically hindered secondary alcohols which are generally difficult to oxidise.¹⁵ A TEMPO (up to 10 %) mediated copper catalysed oxidation was used to provide a convenient method for the oxidation of primary, secondary, allylic and benzylic alcohols. The reaction is carried out in the presence of a perfluorinated bipyridine ligand. They were able to demonstrate selective oxidations of *cis-trans* mixtures of cyclohexanols (Scheme 3). Treatment of a 47:53 *cis-trans* mixture of 4-methylcyclohexanol leads to a selective oxidation of the *cis*-4-methylcyclohexanol whereas the *trans*-4-methylcyclohexanol remains unreacted. The difference in reactivity can be explained by the oxoammonium cation which reacts rapidly with both the *cis* and *trans* isomers, but it is the axial alcohol

that undergoes a faster elimination due to steric hindrance compared to the equatorial intermediate.

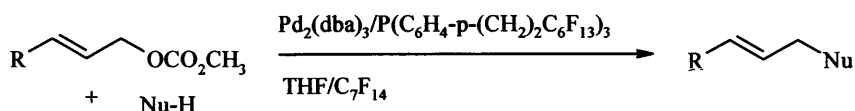


Scheme 3 Selectivity in 4-methylcyclohexanol oxidation.

Another area which is receiving a large amount of interest is the use of perfluorinated palladium complexes for their application in cross coupling reactions. Palladium cross coupling reactions can cause problems with the removal of the catalyst at the end of the reaction. By using perfluorinated palladium complexes, recovery can be obtained by simple liquid-liquid (organic/fluorous) extractions. Reactions which have been investigated include the Negishi, Sonogashira, Suzuki, Heck and finally Stille reactions.²⁴⁻

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One example is the allylic nucleophilic substitution using palladium cross coupling conditions (Scheme 4).²⁹ In order to use the fluoruous biphasic route a fluoruous phase soluble palladium catalyst was made *in situ* by treating $[\text{Pd}_2(\text{dba})_3]$ with the fluorinated phosphine, $\text{P}(\text{C}_6\text{H}_4\text{-4-C}_2\text{H}_4\text{C}_6\text{F}_{13})_3$, in perfluoromethylcyclohexane. The reaction between the cinnamyl methyl carbonate and various nucleophiles was carried out in a THF/ C_7F_{14} biphasic solution at 25 °C or 50 °C for 15 to 80 minutes. The group demonstrated that palladium catalysed allylations were performed effectively using fluoruous biphasic catalysis. Recycling of the catalysts was simple to carry out and a decrease in conversion was only observed after the ninth run (5 mol % catalyst loading). It was found that a reduction of the catalyst loading to 1 mol % gave five quantitative recycling runs.



Scheme 4 Palladium catalysed nucleophilic substitution

The synthesis of Lewis acid catalysts containing tris(perfluorooctanesulfonyl)methide ponytails has been carried out by Nishikido *et al.*, and can be immobilised into the fluoruous phase.³⁰ These compounds can then act as efficient Lewis acid catalysts for alcohol acylation, Fiedel-Crafts acylation, Diels-Alder reactions, transesterification and direct esterification. The first reaction investigated was the Baeyer-Villiger oxidation using H₂O₂ and adamantanone with several different Lewis acid catalysts. Nishikido and co-workers found that the ligands containing a higher fluorine content gave the best yields and best TOF than the simple –OSO₂CF₃ ligand. They also found that their lanthanide catalysts were completely immobilised in the fluoruous phase and could be reused without a drop in reactivity. Several other substrates, cyclobutanone and cyclohexanone, were also tested with the catalysts and gave good selectivities and conversions. More recently, Mikami *et al.* introduced the development of a continuous-flow reactor system using these Lewis acid catalysts under fluoruous biphasic conditions.³¹

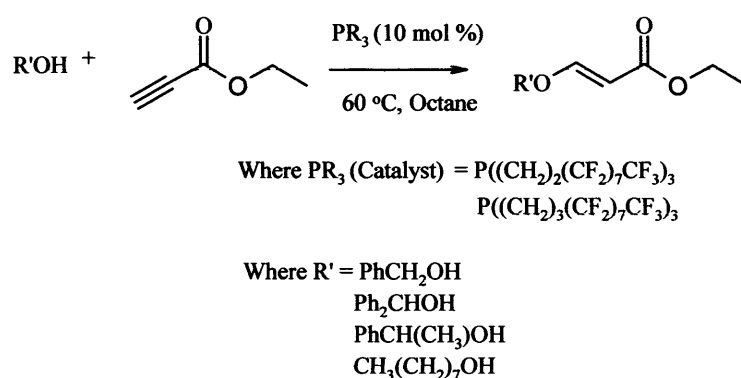
In conclusion, fluoruous biphasic catalysis is a simple process, which can be applied to a wide range of systems. There are many advantages over the aqueous biphasic system, including the ability to use moisture-sensitive substrates and catalysts, also mass transfer is increased and the solubility of gases in perfluorocarbon solvents is higher than in organic solvents. There are, however, disadvantages of the fluoruous biphasic system: 1) catalyst leaching is apparent in some systems and, 2) perfluorocarbon solvents are expensive and environmentally persistent. Assuming that the perfluorocarbon solvent can be recycled and the leaching of the catalyst is minimal, then the potential of these systems for commercial use is still evident.

1.2 Fluoruous Catalysis without Perfluorocarbon Solvents

Perfluorocarbon solvents offer certain advantages for catalysis reactions, but they are also accompanied by a number of disadvantages as described above. Hence, it would be

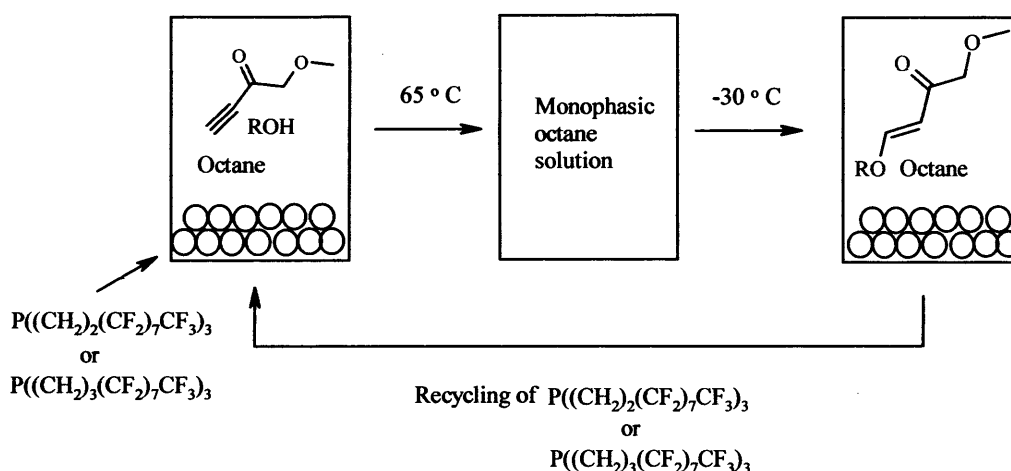
beneficial to be able to carry out the separation and recovery of a fluorous-tagged catalyst without the need for perfluorocarbon solvents.

An area that has recently been developed exploits the thermomorphic behaviour of fluorous catalysts. Gladysz first introduced this area of research in 2001,^{32, 33} by demonstrating the temperature dependent solubility of the fluorous catalyst in octane. The trialkylphosphine is soluble in octane at 60 °C under the reaction conditions shown in the addition reaction in Scheme 5, but it has very low solubility in octane at 0 °C or below.



Scheme 5 Phosphine – catalyzed addition reaction

At the end of the reaction the fluorous phosphine was precipitated out of solution by cooling to -30 °C, thus the products were obtained by decantation of the supernatant organic solvent whilst the catalyst was recycled and reused (Scheme 6). All of the phosphines tested showed that 90% of the activity could be maintained from cycle to cycle after three consecutive runs. This unique behaviour provides a novel method for catalyst recycling and it is essential that the fluorous reagent has an extremely low solubility in the organic solvent at low temperatures for good separation to occur.



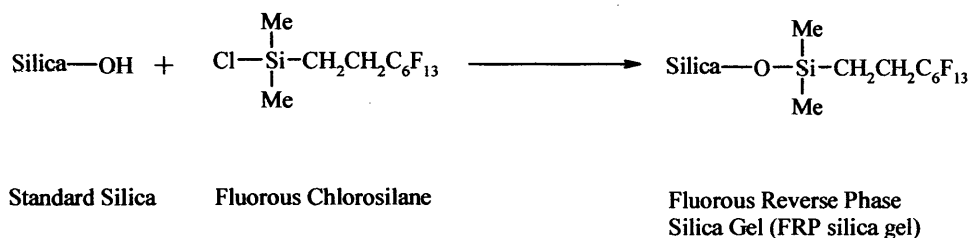
Scheme 6 Thermomorphic fluorine catalysis.

Gladysz extended his thermomorphic work on fluorine phosphines to incorporate the use of commercial Teflon tape as an insoluble fluorine support that improves catalyst recovery, separation and catalyst delivery.³⁴ Gladysz *et al.*, tested ketone hydrosilylation reactions using fluorine rhodium complexes that usually have little or no solubility in standard organic solvents at room temperature; however, their solubility increases with increasing temperature. The catalyst loading was 0.15 mol % and homogeneous conditions in dibutylether were obtained at 55 °C with Teflon tape (thickness/width 0.0075/12 mm) becoming slightly discoloured during the reaction. When the reaction mixture was cooled to -30 °C at the end of the reaction, the fluorine catalyst phase separates onto the Teflon tape turning it orange-red. GC analysis indicated that 97 % of the hydrosilylated ketone was obtained in the first cycle; however loss of activity was apparent on the third and fourth cycles (96 and 65 % respectively). The loss in activity was attributed to catalyst deactivation and not leaching. In summary to the work carried out by Gladysz, it is apparent that attractive interactions between the fluorine domains are occurring.

In 2001 Yamamoto *et al.* also demonstrated independently the thermomorphic behaviour of 3, 5-bis(perfluorodecyl)phenylboronic acid. This is an excellent Lewis acid catalyst for amide condensation and is insoluble in *o*-xylene at room temperature but becomes soluble under refluxing conditions.³⁵ Yamamoto has since developed a super Brønsted acid which can also be recycled.³⁶

Recently, Mikami's group have demonstrated the temperature dependent solubility of fluorous super acids, such as the lanthanide tris(perfluorooctanesulfonyl)methide and perfluorooctanesulfonimide complexes in organic solvents.³⁷ These complexes can be used for Friedel-Crafts acylation reactions without fluorous solvents. After the reaction, the ytterbium complex precipitates out of solution at -20 °C. The liquid phase was decanted and the residual lanthanide complex was reused without isolation. No loss of activity was observed.

Recently, Bannwarth *et al.* have investigated fluorous catalysis without the requirement for perfluorocarbon solvents.³⁸ This approach entails the immobilization of the fluorous derivatised catalyst onto fluorous reverse phase silica gel. Fluorous reverse phase silica gel (FRPSG) contains a fluorous bonded phase and is made by the reaction of standard silica gel with a fluorous chlorosilane to form a covalent linkage as shown in Scheme 7.³⁹ They first reported the immobilisation of bis(triphenylphosphine)palladium complexes containing perfluorocarbon groups onto fluorous silica gel and their successful application in the Suzuki and Sonogashira carbon – carbon coupling reactions.



Scheme 7 Preparation of FRP Silica Gel

The two fluorous solid supports shown in Figure 6 were prepared and added to a solution of the desired complex in diethyl ether and hexafluorobenzene and the solvent was removed. Catalyst loadings of 0.001, 0.01, 0.1 and 1.5 mol % were examined in the Suzuki reaction. The best results were obtained when the catalyst loadings were 0.01 mol % and above giving >98 % yields with successful recycling. A lower catalyst loading of 0.001 mol % showed complete conversion, though a reduced yield of 86 % was obtained. The efficiency of the recycling was also reduced, and in the second run a lower yield of 45% was obtained.

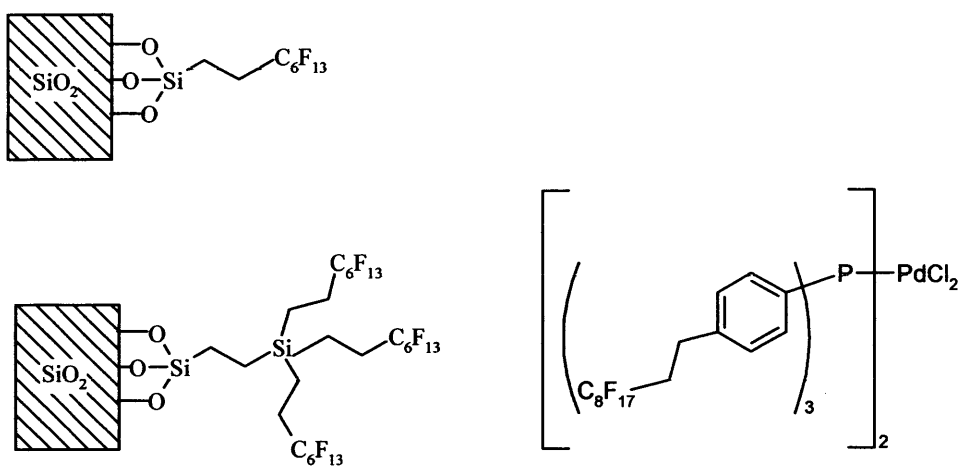
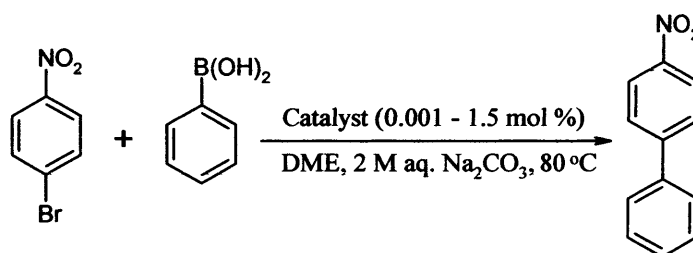


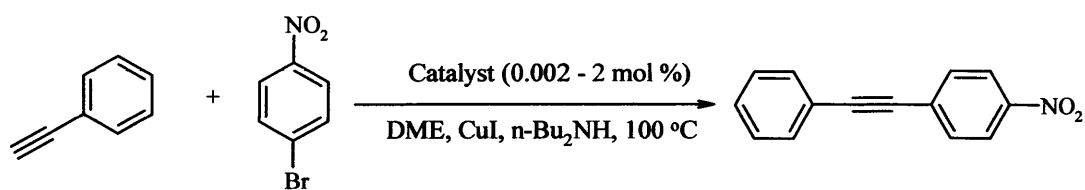
Figure 6 Fluorous Solid Supports and palladium complex

To see if the reaction was sensitive to a variety of functionalities, Bannwarth *et al.* tested the Suzuki reaction (Scheme 8) with different substrates. They found that electron deficient aryl bromides reacted with aryl boronic acids to give high yields and good recycling. However, some functionalities showed a significant decrease in activity. For example, 3-thienylboronic acid, which showed high conversions in the first run, gave only the aryl bromide in consecutive runs, demonstrating complete loss of activity because of poisoning of the catalyst by thiophene.



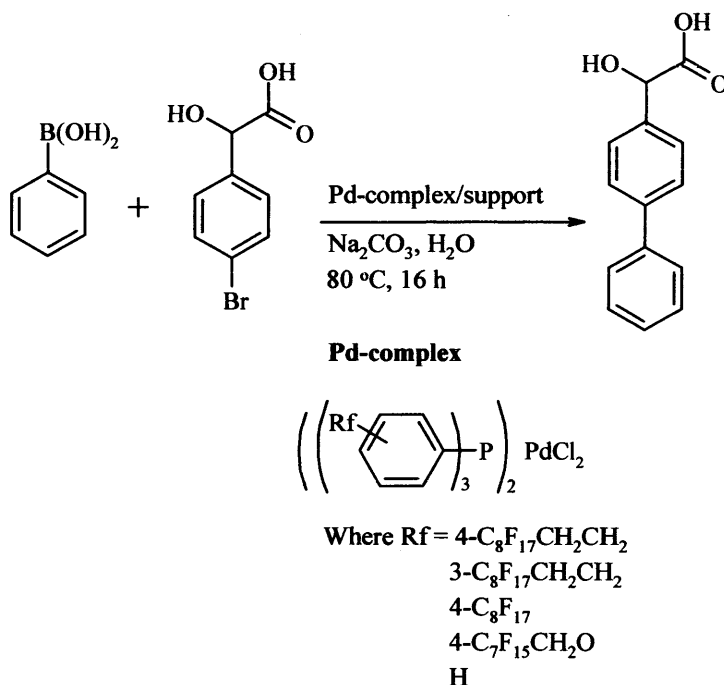
Scheme 8 Suzuki reactions performed with supported palladium complex.

A higher catalyst loading of 2 mol % was required to give high yields and reasonable recycling results for the Sonogashira reaction (Scheme 9). With 0.2 mol % catalyst loading, a high yield of >98 % was obtained, but when the catalyst was recycled the yield declined considerably on the second (30 %) and third run (0 %).



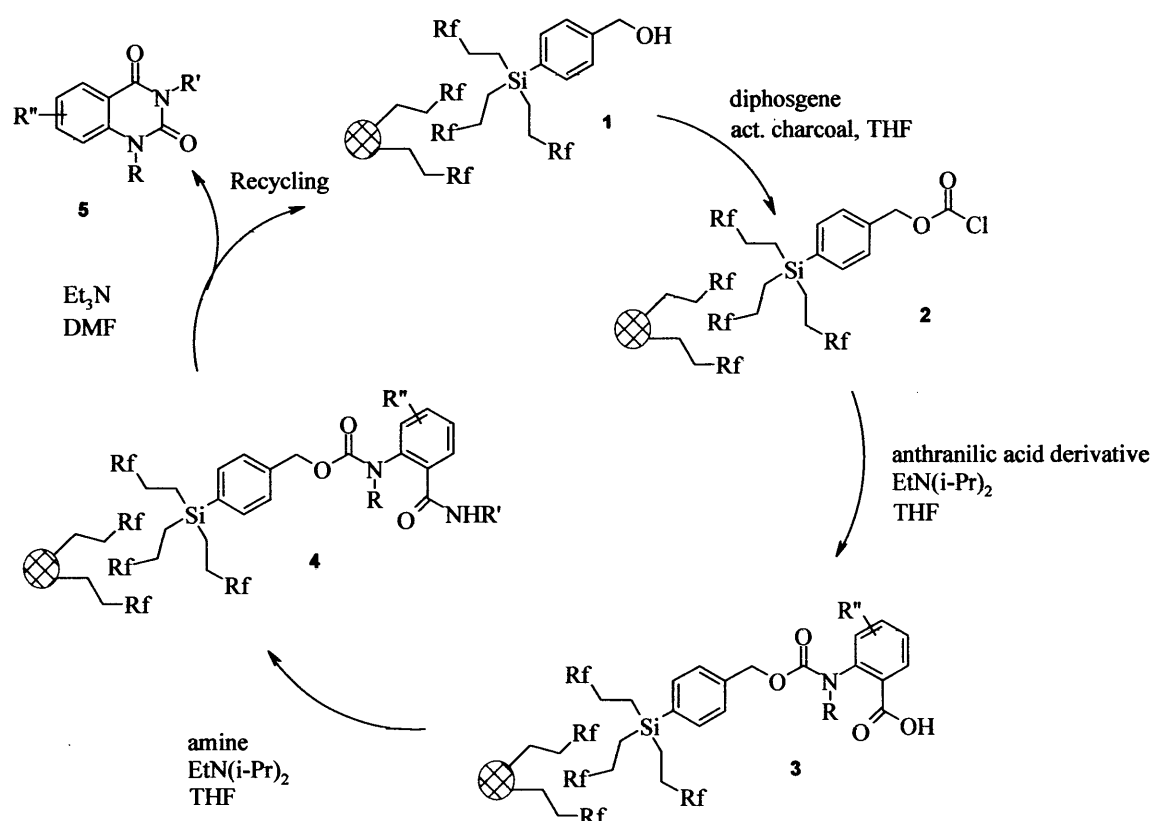
Scheme 9 Sonogashira reaction with supported palladium complex.

Bannwarth has also carried out Suzuki coupling reactions in water (Scheme 10) using fluorosilica supported perfluoro-tagged palladium complexes.⁴⁰ Initially, 0.001 mol % - 1 mol% of the perfluoro-tagged catalyst was tested in the Suzuki reaction of phenylboronic acid and *p*-bromomandelic acid in water. The product was efficiently separated by filtration and the catalyst was recovered and reused up to five times. Conversions were found to be low with the yields deviating significantly from the first run (27 %, 71 %, 54 %, 37 %, 22%, and 7 %) with 0.001 mol % catalyst loading. When this is compared to higher catalyst loadings, 0.1 mol % and 1.0 mol %, no variation from the first run was found to occur and nearly complete conversion was seen in up to the fifth run. Minimal leaching of Palladium was found to occur (2.2 ppm corresponding to 0.8 % of palladium).



Scheme 10 Suzuki reaction using a fluorosilica supported perfluoro-tagged palladium complex.

Bannwarth also published a multistep parallel synthesis of quinazoline-2,4-diones. The reaction involves the adsorption of a perfluoro-tagged benzyl alcohol onto fluororous reverse phase silica gel⁴¹ by evaporating a solution of **1** onto FRP silica gel in the presence of diethyl ether to yield the active support (Scheme 11). The benzyl alcohol **1** was first reacted with diphosgene to give **2**. The reaction mixture was then split into batches to allow the reaction with different anthranilic acids in the presence of base to yield **3**. Again, this mixture was split into four parts in order to react with the required primary amine to produce a small series of **4**. Cyclisation was the final step which was induced by the reaction of **4** with Et₃N to give the desired products **5**. This multistep synthesis avoids the isolation of reaction intermediates and affords pure product when separated from the FRP silica gel. The reaction steps were carried out in THF which causes the release of the perfluoro-tagged benzyl alcohol into the solvent. After each reaction step the solvent is evaporated and the support taken back into a mixture of CH₃CN/H₂O and filtered. This solvent switch causes reattachment of intermediates back onto the support.



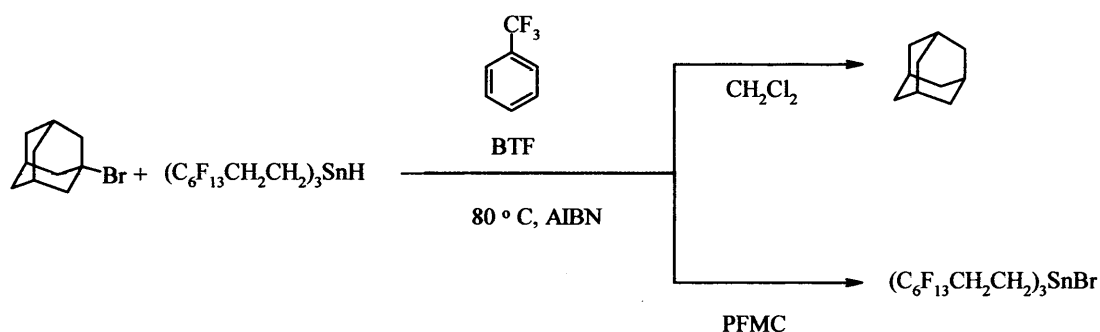
Scheme 11 Synthesis of quinazoline-2,4-diones starting from FRPSG – immobilised benzyl alcohol

Biffis *et al.*, have developed a green protocol for the silylation of alcohols using bonded fluororous phase catalysis.⁴² Dirhodium(II) perfluorocarboxylate was loaded onto a functionalised silica surface – 1*H*,1*H*,2*H*,2*H*-perfluorodecyldimethylchlorosilane. The absorption process is fully reversible and the metal complex could be removed by washing with diethyl ether. The supported dirhodium(II) perfluorocarboxylate was tested in a model reaction, the triethylsilane alcoholysis with 1-octanol. The catalysts were active under these conditions; however, the supported metal complex underwent deactivation which was observed by a change in colour from light green to brown after the first few hours into the reaction. The same reaction was carried out with no solvent present giving an extremely efficient reaction with significant increases in catalyst productivities. The metal catalyst was simply recovered by filtration and subsequently recycled. Analysis of the filtrate found 2.6 % of the metal catalyst in the liquid phase after the first cycle which remained constant throughout the recycling.

1.3 Organic Synthesis: Liquid – Liquid Separation

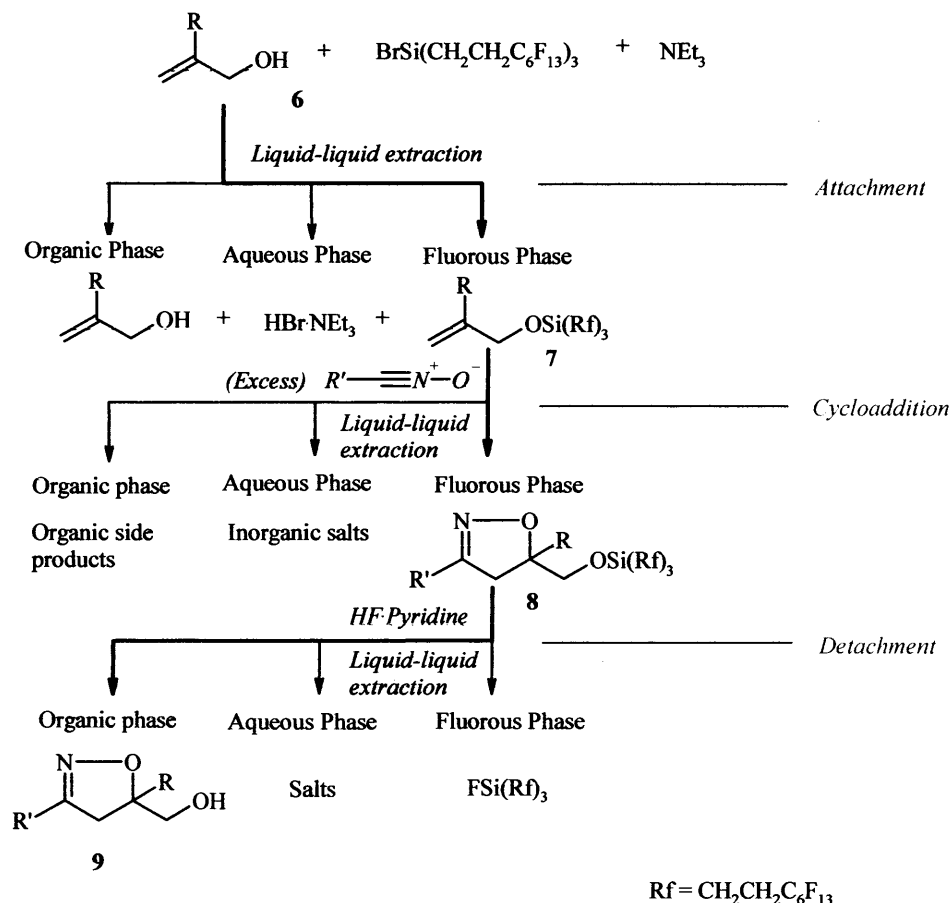
The most time consuming part of performing organic reactions is often the purification step. In order to simplify purification Curran has utilised and further developed fluorous biphasic systems.⁴³ Reagents, reactants or catalysts are labelled with a fluorous component, which will render the compound soluble in the fluorous phase at the end of the reaction. An example is the fluorous tin hydride, $(\text{C}_6\text{F}_{13}\text{CH}_2\text{CH}_2)_3\text{SnH}$, which contains three fluorous ponytails. The fluorous tag must have sufficient fluorine content, usually containing a minimum of 60% fluorine, to induce tagged molecules to partition into the fluorous phase at the purification stage and to be readily separated from untagged molecules by liquid - liquid separation.

Although benzotrifluoride is not a fluorous solvent since it is miscible with a number of organic solvents, it has proved to be invaluable as a solvent for fluorous synthesis since it has the ability to dissolve fluorous compounds as well as organic compounds. At the end of the reaction, the benzotrifluoride is removed and the reaction mixture is then partitioned between a perfluorocarbon solvent and an organic solvent. An example of the use of benzotrifluoride is in the reaction of adamantyl bromide with a fluorous tin hydride and AIBN (Scheme 12) to give a 90 % yield of adamantane; 95 % of tin bromide was recovered.^{44,45} Upon reaction with LiAlH_4 , the fluorous tin bromide can be reduced to the active tin hydride which can be recycled and reused.



Scheme 12 Reaction of adamantyl bromide and fluorous tin hydride.

One reaction that was first tested to demonstrate the potential of fluorous synthesis was the 1, 3-dipolar cycloadditions of nitrile oxide to alkenes and alkynes.⁴⁴ The main reaction scheme is outlined in Scheme 13 with each step purified by a three phase extraction between the organic phase, water and a fluorous phase.



Scheme 13 Synthesis of isoxazoline

The process involves an allyl alcohol which is rendered fluorous by silylation with a highly fluorinated silyl halide. The excess alcohol is required to push the reaction to completion and any excess is taken into the organic phase. The cycloaddition is then conducted by a Mukaiyama method with a large excess of the nitrile oxide and phenyl isocyanate in order to form the nitrile oxide *in situ* and hence the fluorous isoxazoline **8**. Desilylation of **8** returns the final product **9** to the organic phase. The nitrile oxide cycloadditions requires protection of the alcohol, which would otherwise react with the isocyanate and this has been exemplified by using a fluorous silyl group.

1.4 Fluorous Solid Phase Extraction

Curran's early work on fluorous synthesis concentrated on using highly fluorinated compounds (60 – 120 fluorine atoms) to ensure good separation by liquid–liquid extraction, but these perfluoroalkylated compounds had little or no solubility in organic solvents, so finding suitable solvents for synthetic reactions became difficult. Recently, Curran and co-workers introduced the concept of light fluorous syntheses which requires less fluorine and uses solid phase extraction with fluorous reverse phase (FRP) silica gel at the separation stage.^{47,48} The use of fluorous reagents or catalysts that have fewer fluorine atoms allows the compounds to have improved solubility in organic solvents, thus allowing a wider variety of solvent choice for a reaction system.

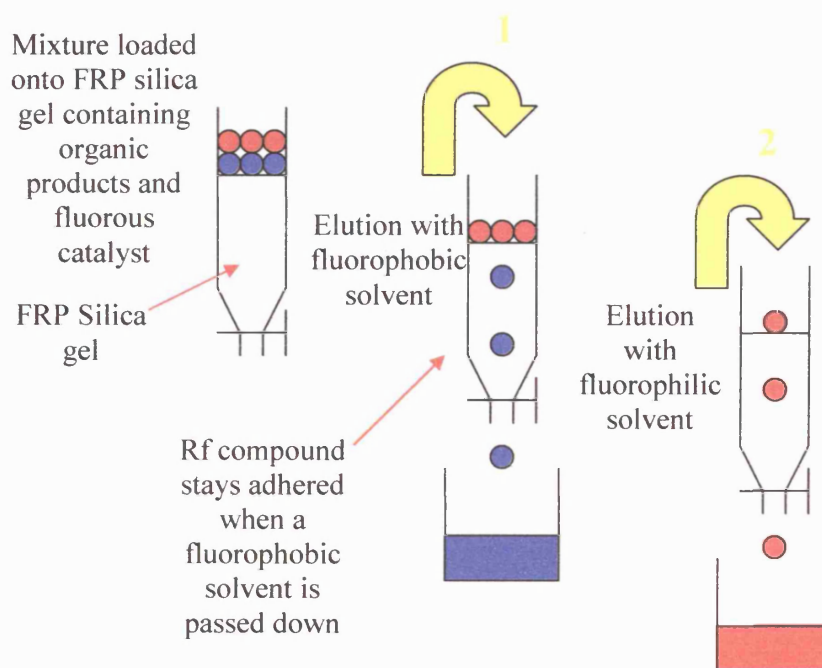
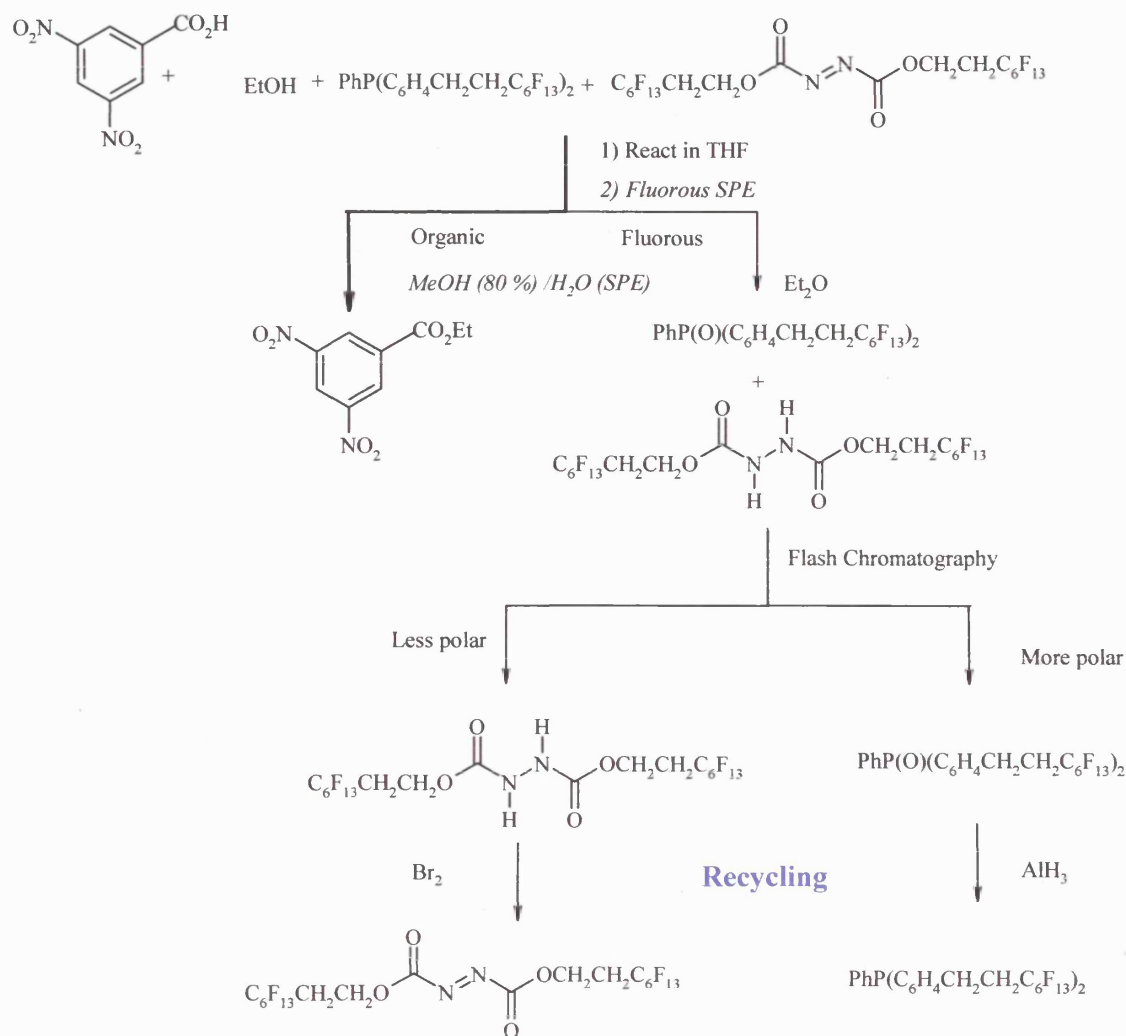


Figure 7 Fluorous solid phase extraction.

Solid phase extraction (SPE) involves loading a crude reaction mixture onto a column of fluorous reverse phase silica (FRP silica gel) (Figure 7). By using a fluorophobic solvent (e.g. MeOH/H₂O mixture) the non-fluorous components of the mixture will be removed. Depending on the design of the reaction, the organic fraction collected is normally the

organic product.⁴⁹ A solvent such as THF is then used to remove and recover the fluorous compounds. Solid phase extraction has been used in a number of parallel syntheses in which fluorous reagents,⁵⁰ fluorous ligands⁵¹ and fluorous protecting groups⁵² have all been incorporated.

A recent application of FSPE using fluorous reverse phase silica gel was for the purification of the organic product in the fluorous Mitsunobu reaction.⁵³ The reaction used a fluorous triphenylphosphine, $\text{PhP}(\text{C}_6\text{H}_4\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_2$ and a fluorous diethylazodicarboxylate (DEAD) reagent. The $\text{PhP}(\text{C}_6\text{H}_4\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_2$ underwent a trial run with a standard DEAD reagent with the results clearly showing that this particular phosphine was suitable and effective in the Mitsunobu reaction. In order to complement the entire reaction, a fluorous DEAD reagent was prepared and it was decided to test both fluorous compounds in the Mitsunobu reaction in order to remove the fluorous phosphine oxide and hydrazine byproducts. 3, 5-Dinitrobenzoic acid, ethanol and the fluorous phosphine were reacted together for 16 hours, the solvent was removed and the crude reaction mixture loaded on to fluorous silica gel where elution with methanol (80 %)/H₂O (20 %) gave the Mitsunobu product in 92 % yield. Further elution with diethyl ether allowed the recovery of both the fluorous phosphine oxide and the fluorous hydrazine. Once both fluorous components had been recovered, they could then be separated simply by passing down a flash column since the fluorous hydrazine is less polar in comparison to the phosphine oxide. Recycling of these products was accomplished as shown in Scheme 14.



Scheme 14 Fluorous Mitsunobu.

Several second generation fluoruous DEAD reagents have now been synthesised. It was found that the original DEAD reagent combined with a fluoruous phosphine did not perform as well as the standard reagents (DIAD and TPP).⁵⁴ Curran took the reaction of 4-(4-nitrophenyl)butyric acid with 3,3-dimethylbutanol and carried out four reactions using the standard TPP and DIAD reagents as well as the fluoruous analogues. A 100 % yield detected by GC was formed using the TPP and DIAD whereas there was no product formed using both fluoruous analogues. When the reaction was promoted with TPP and F-DEAD a 92 % yield was obtained and the same result was obtained with F-TPP and DIAD. This insinuated that the F-DEAD was inferior to DIAD in Mitsunobu reactions. The group synthesised a series of new DEAD reagents (Figure 8) and analysed their retention on

HPLC to understand their separation behaviour. Curran found that F-DEAD-2 and F-DEAD-3 gave much better yields (92-99 %) in the reaction of 4-(4-nitrophenyl)butyric acid with 3,3-dimethylbutanol compared to F-DEAD-1 and separation of the crude reaction material could be obtained by FSPE .

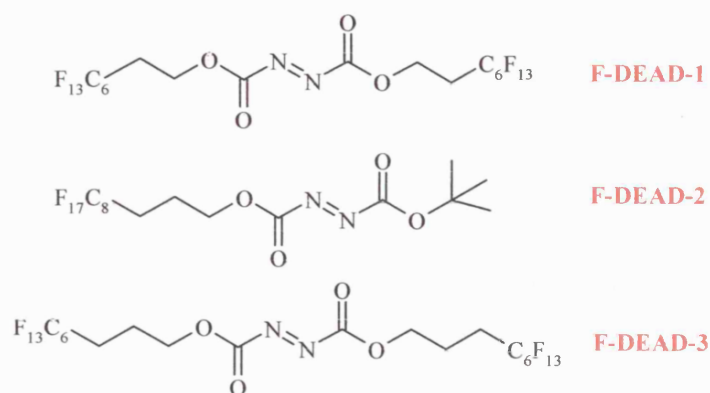


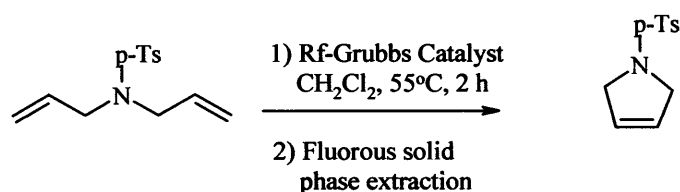
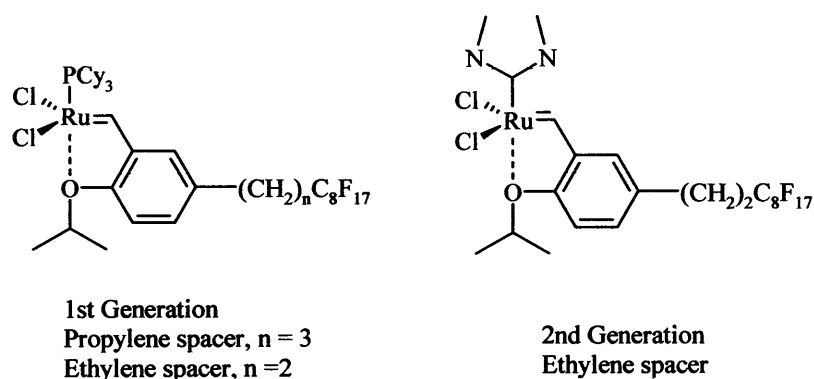
Figure 8 Fluorous DEAD reagents.

The use of fluorous solid phase extraction allows uncomplicated and efficient work up of reactions and has been recognized for its successful use in parallel synthesis and hence, its application to combinatorial chemistry. A variety of fluorous reagents have now been prepared for their use in light fluorous syntheses where FSPE is used at the separation stage and these include organotin compounds, coupling agents, oxidising and reducing agents.⁵⁵

Stuart and Hope have elegantly shown separation, recovery and recycling of a fluorous-tagged nickel catalyst, $[\text{Ni}(\text{F}_{13}\text{C}_6\text{C}(\text{O})\text{CHC}(\text{O})\text{C}_6\text{F}_{13})_2]$, using fluorous-solid phase extraction.⁵⁶ The Lewis acid catalysed reaction between β -diketones and ethylcyanoformate using several nickel catalysts, $[\text{Ni}(\text{acac})_2]$, $[\text{Ni}(\text{hfacac})_2]$, $[\text{Ni}(\text{F}_3\text{CC}(\text{O})\text{CHC}(\text{O})\text{CF}_3)_2]$ and $[\text{Ni}(\text{F}_{13}\text{C}_6\text{C}(\text{O})\text{CHC}(\text{O})\text{C}_6\text{F}_{13})_2]$ was studied. It was found that $[\text{Ni}(\text{F}_3\text{CC}(\text{O})\text{CHC}(\text{O})\text{CF}_3)_2]$ and $[\text{Ni}(\text{F}_{13}\text{C}_6\text{C}(\text{O})\text{CHC}(\text{O})\text{C}_6\text{F}_{13})_2]$, showed good activity compared to $[\text{Ni}(\text{acac})_2]$. Separation and recovery of the fluorous-tagged nickel complexes was carried out by passing the reaction mixture down a short column of fluorous reverse phase silica gel. No leaching of the green fluorous-tagged nickel complex, $[\text{Ni}(\text{F}_{13}\text{C}_6\text{C}(\text{O})\text{CHC}(\text{O})\text{C}_6\text{F}_{13})_2]$, was observed on the column, whilst the organic products were removed successfully with DCM; switching to diethyl ether afforded the nickel catalyst quantitatively. The catalyst was then washed with hexane and dried before being

reused four times with isolated yields of 91 %, 84 %, 82 %, 67 % and 52 %. The drop in yield was accounted for by the catalyst undergoing decomposition.

Curran has prepared light fluoruous analogues of Grubb's catalyst which incorporates perfluoroalkyl groups into the ligands. These light fluoruous Grubb's catalysts can be successfully recovered by solid phase extraction on fluoruous silica gel (Scheme 15).⁵⁷ The reaction, separation and reuse was studied for the conversion of *N,N*-diallyl-*p*-toluenesulfonamide to *N-p*-tosyl-2,5-dihydro-1*H*-pyrrole. The first generation fluoruous derivatised catalyst which contained the propylene spacer group (Scheme 15) was the first catalyst to be tested giving 98-99 % of the product *N-p*-tosyl-2,5-dihydro-1*H*-pyrrole. Separation was carried out by loading the crude reaction mixture onto fluoruous silica gel which was then eluted with acetonitrile to provide the organic compounds followed by ether to provide the fluoruous fraction. The first generation catalyst containing the ethylene spacer group was also tested and found to give comparable yields of the product *N-p*-tosyl-2,5-dihydro-1*H*-pyrrole, 99 %. The catalyst was re-used seven times and the yield of the catalyst recovered ranged from 88 % on the first recovery and 69 % on the seventh recovery. The second generation catalyst also behaved in a similar manner with good product yields obtained, 94 – 98 %. Five successive recycles with the second generation catalyst was carried out, however, optimised separation on fluoruous silica gel was required. A mixture of 80 % methanol and water and THF ensured good recovery of this catalyst, 91 % on the first recovery and 85 % on the fifth recovery. During the reaction, some rhodium leaching was observed with all the light fluoruous derivatised Grubb's catalyst and was caused by the dissociation of rhodium from the carbene ligand during the reaction. This inevitably leads to leaching in the final product; however, levels of contamination are within tolerable limits and can be further reduced by chromatography or crystallisation.



Scheme 15 Examples of light fluorous derivatised Grubbs' Catalyst together with an exemplar reaction for the formation of the product, *N*-*p*-tosyl-2,5-dihydro-1*H*-pyrrole using the light fluorous Grubbs catalysts.

More recently, Curran *et al.* have introduced the novel separation of organic compounds from fluorous compounds by reverse fluorous solid – phase extraction (R-FSPE, Figure 9). This process uses standard silica gel (not FRP silica gel) and is the reverse of fluorous solid phase extraction. The crude reaction mixture is charged onto a polar solid phase, standard silica gel, and the column is eluted with a fluorous solvent to collect the fluorous compounds whilst the organic components are retained by the silica column. Curran *et al.*, investigated allylation reactions using perfluoroalkyl iodides with allyl stannanes to give the perfluoroalkanes using R-FSPE. The allylated products (fluorous) were separated from the residual tin compounds (organic) by R-FSPE in 62 – 85 % yield free from reagents and byproducts.

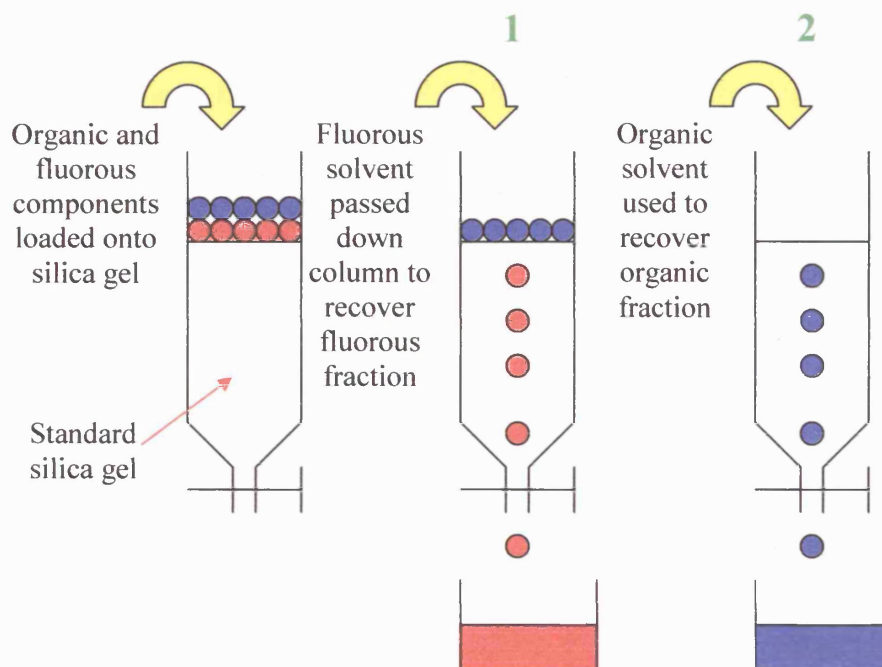


Figure 9 R-FSPE

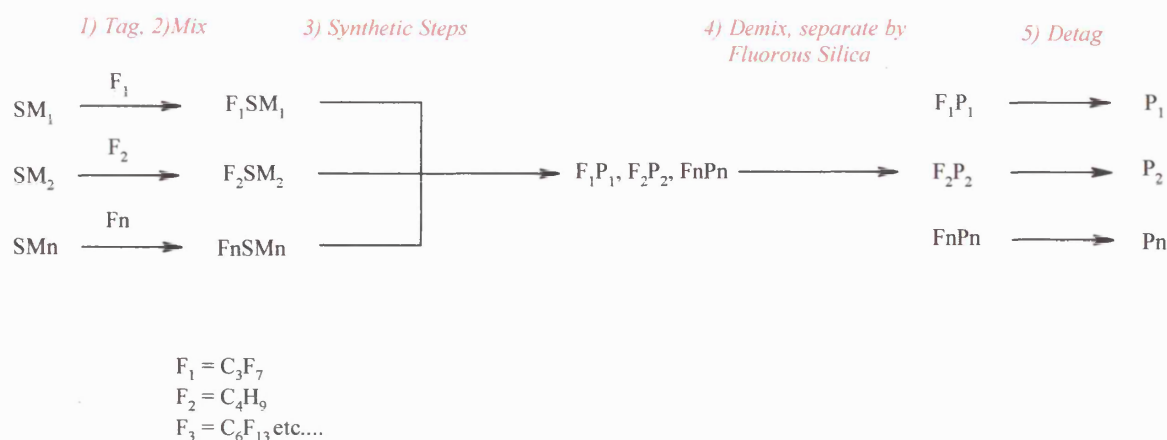
Overall, the above examples demonstrate the feasibility and easy use of fluoros solid phase extraction as a separation technique in fluoros syntheses. It also demonstrates that with reaction planning, the desired product can be finely tuned to have a greater affinity for one particular solvent over another.

1.5 Fluorous Mixture Synthesis⁵⁵

Over the past ten to eleven years a variety of reactions within the field of fluoros chemistry have been investigated with attention focused on the ability to separate products from reactants/catalysts/byproducts. Recently, fluoros mixture synthesis was developed in order to synthesise large libraries of compounds taking advantage of the novel separation techniques associated with light fluoros chemistry.⁵⁹ The process for developing a fluoros mixture synthesis involves a carefully planned series of steps as will be described below.

Fluorous Mixture Synthesis (FMS) consists of five different steps: 1) each substrate (SM_1 , SM_2 SM_n) is tagged with an individual fluoros label of different fluoros content (F_1SM_1 , F_2SM_2 F_nSM_n where $F_1 = C_3F_7$, $F_2 = C_4F_9$, $F_3 = C_6F_{13}$ etc); 2) the newly

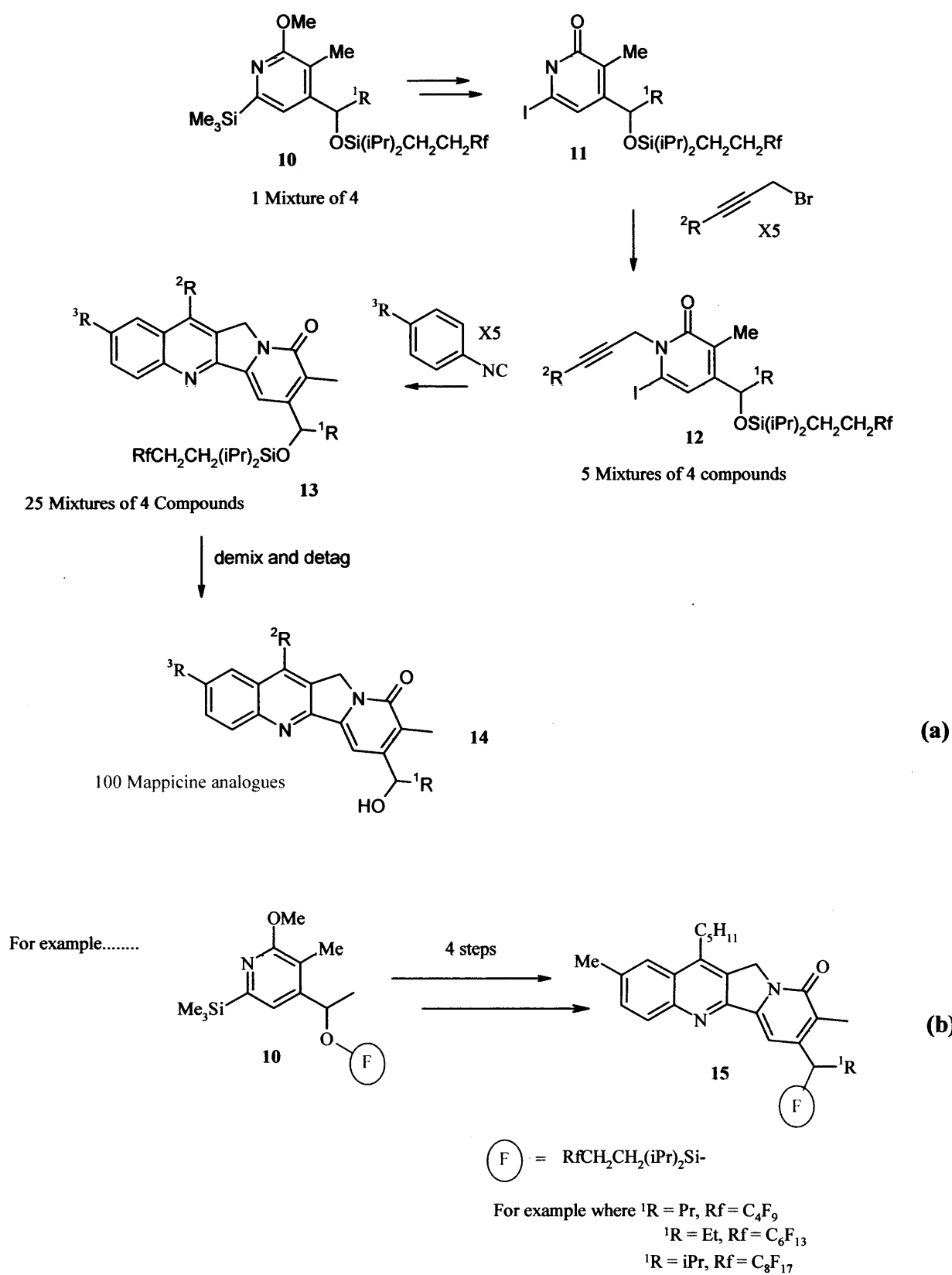
derivatised fluororous substrates are then mixed together; 3) the mixed substrates are sequentially taken through a multistep synthesis; 4) the penultimate step involves demixing and separating by fluororous chromatography (eluting in order of increasing fluorine content) to give individually pure fluororous products; 5) the products are then finally detagged to give a library of the final products (Scheme 16).



Scheme 16 Overview of fluororous mixture synthesis.

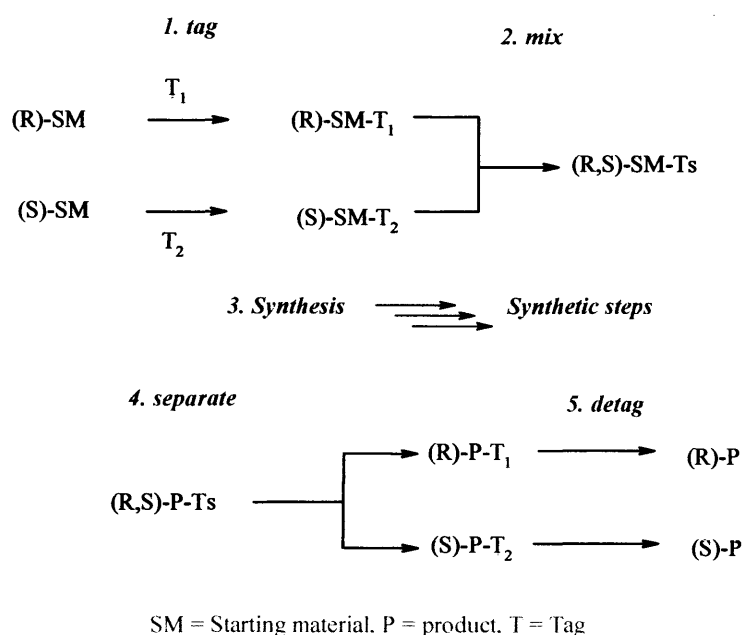
The first FMS was carried out by Curran *et al.* in 2001 when they constructed a 100 membered fluororous tagged Mappicine library.⁵⁹ Four different pyridines were each individually labelled with a different length of perfluoroalkyl group and then mixed together before being taken through the four step synthesis depicted in Scheme 17. The pyridine **10** undergoes an iododesilylation and demethylation to give **11** which can in turn undergo N-propargylation to give **12**. This is finally reacted with an isonitrile derivative to give the desired Mappicine analogues (an example of a fluororous tagged analogue is shown in Scheme 17 (b)). The final stage involves demixing and detagging to give analogues of the natural compound, Mappicine. A total of 25 four component mixtures were reported to have been prepared, demixed and detagged. The analogues were demixed based on their fluorine content by fluororous high pressure liquid chromatography (F-HPLC) (where the stationary phase silica is derivatised with fluororous groups) as demonstrated by the Mappicine analogues in Scheme 17 (b). The analogue that contains a C_4F_9 unit was the first to be detected at approximately 20 minutes whilst the C_8F_{17} unit analogue was the last to be detected at approximately 36 minutes.

Realising the powerful potential of FMS Curran decided to apply this to the preparation of a 560-membered library of Mappicine analogues. The synthesis was exactly the same as shown in Scheme 17 (a), except that a total of 560 individual Mappicine analogues were prepared.⁶⁰ The synthesis of this library of compounds was achieved in just 90 steps which is a significant improvement when compared to 630 steps required for the parallel synthesis.



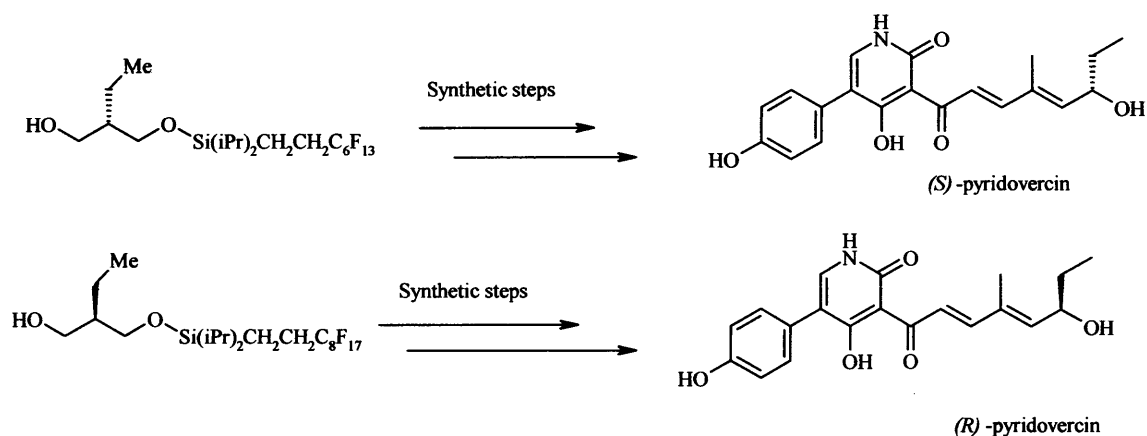
Scheme 17 Fluorous mixture synthesis of Mappicine Analogues.

Fluorous mixture synthesis has been adapted for quasiracemic syntheses.^{60,61} Classical racemic synthesis prepares both enantiomers of a compound in a single synthesis, but purification and separation are challenging. Quasiracemic synthesis involves the use of enantiopure starting materials, and ends with enantiopure products. These quasienantiomers are tagged with a fluorous label to give improved separation and purification at the end of the reaction (Scheme 18).



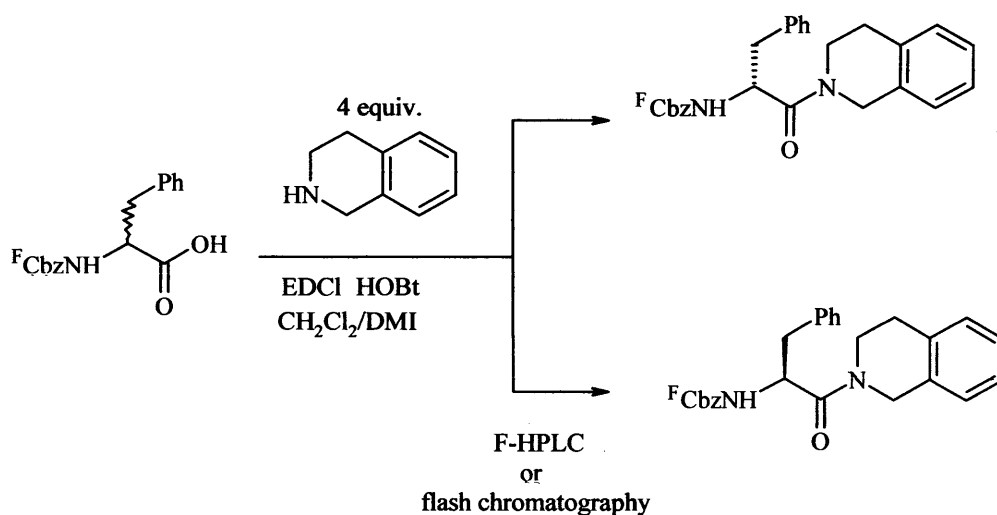
Scheme 18 Quasiracemic synthesis by fluorous tagging.

One quasiracemic reaction that was carried out was the synthesis of pyridovericin.⁶¹ Curran *et al* prepared the corresponding fluorous (*R*) and (*S*) enantiomers of the starting material required for the synthesis of pyridovericin. The enantiomers were each individually attached with a different fluorous silane; the fluorous section of the molecule consisting of a C₆F₁₃ and a C₈F₁₇ unit. These enantiomers were then mixed together and taken through a multistep synthesis. The two enantiomers were finally separated by fluorine content using HPLC on a Fluofix column, and the tags removed to give both the (*R*) and (*S*) enantiomers of pyridovericin (Scheme 19).



Scheme 19 Quasiracemic synthesis of (*R*)- and (*S*)- Pyridovericin

Quasiracemates of amino acids have also been prepared using the fluorous benzyl carbamates, ^FCbz , as the fluorous tag (Scheme 20).⁶² The same method for the synthesis of (*R*)- and (*S*)- pyridovericin was used, however in this case, natural L and D enantiomers were given the C_8F_{17} or C_6F_{13} fluorinated tag. Coupling of the tetrahydroisoquinoline with the quasiracemate phenylalanine gives the crude reaction product which can be subjected to demixing by either flash or HPLC chromatography to give the D and L enantiomers. It was found that HPLC gave better yields, 81-83 %, of the enantiomers compared to flash chromatography, 66-76 %.

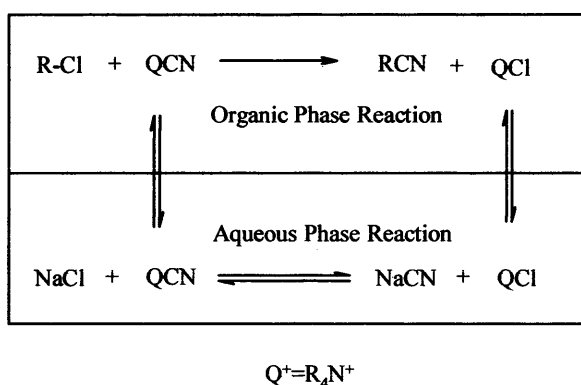


Scheme 20 Coupling and demixing of an amino acid quasiracemate

1.6 Phase Transfer Catalysis (PTC)^{63,64}

Phase transfer catalysis is a vast subject containing more than 1700 patents and 8000 publications with 30 main reaction categories. This unique synthetic method has a wide application which is responsible for a number of commercial phase transfer catalysed reactions with over 600 applications found in industry including the synthesis of polymers, dyes, agrochemicals, perfumes and many more. Phase transfer catalysts offer a number of advantages which include improved environmental performance and enhanced safety.

Phase transfer catalysis was first established in 1970 by Starks and Liotta, and is best represented by Scheme 21.^{65,66} The diagram represents the nucleophilic reaction between 1-chlorooctane and aqueous sodium cyanide in which the two reagents are located in two different phases. Normally, these reagents are inhibited by the inability for the reagents to come into contact, even under forcing conditions. Starks *et al.* demonstrated that an appropriate quaternary salt acts as a shuttling agent, extracting the cyanide anion from the aqueous phase into the organic phase allowing reaction between 1-chlorooctane and the cyanide anion to give the desired nitrile compound. The catalyst is often a quaternary ammonium salt (e.g. tetrabutyl ammonium halide $[\text{C}_4\text{H}_9]_4\text{N}^+\text{X}^-$), and is sometimes referred to as a “quat” and symbolized by Q^+ . Other types of phase transfer catalysts include crown ethers, cryptands and azacrown ethers.⁶⁷ These phase transfer salts have been used successfully in a range of reactions such as nucleophilic displacement reactions, reactions with strong bases, oxidations, reductions, asymmetric synthesis of carbon-carbon bonds and polymerisation.



Scheme 21 Phase transfer catalysed nucleophilic displacement of 1-chlorooctane.

Chemists are also attracted to reaction systems that lack an aqueous phase since side reactions can occur in liquid-liquid systems. Reactions that involve a fluoride ion are typically highly hydrated and have reduced nucleophilicity in liquid-liquid systems.^{68,69} By offering an alternative in which the liquid-liquid system is replaced by a solid-liquid system, a more reactive anion is formed providing a more prominent reaction. However, difficulties are encountered in the formation of a reactive anion, therefore, addition of a third phase, *the omega phase*, increases the rates greatly whereby the lattice of the salt is broken and is freely available to exchange the anion. The amount of water in the system is critical as too much water can be detrimental to a system whilst not enough can lead to slow rates of reactions. When considering a solid-liquid system, catalyst structure, agitation, temperature and nature of the organic solvent are all extremely important factors.

The mechanistic descriptions of solid-liquid systems are not dissimilar to liquid-liquid systems with the first step requiring the transport of the anion from the solid phase into the organic phase using a phase transfer catalyst with crown ethers or cryptands being extremely efficient under these conditions. These catalysts are thermally stable and are active to temperatures of 150-200 °C with no cause for concern under basic or acidic conditions. Examples of multidentate ligands are depicted in Figure 10. The second step requires the reaction of the anion with the substrate in the organic phase. Finally, the last step is the transport of the product anion back to the solid phase and transport of the reagent anion to the organic phase for further cycles. Unfortunately, crown ethers and cryptands are not normally used by industry because they are too expensive.

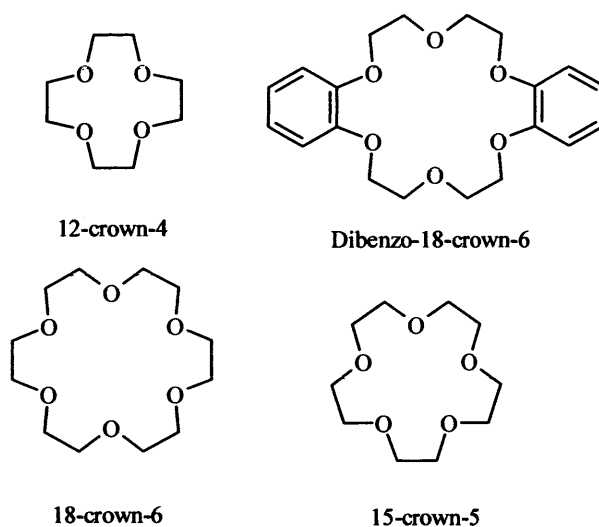
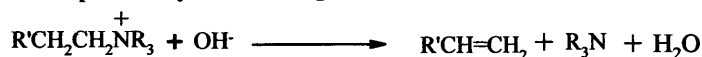


Figure 10 Examples of multidentate ligands

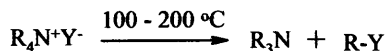
1.7 Nucleophilic Substitution Reactions under Phase Transfer Conditions

Phase transfer catalysis allows an innovative way of carrying out displacement reactions in liquid-liquid or even solid-liquid systems. In displacement reactions it is important to recognize the need for efficient transfer of the nucleophile into the organic phase, which has proven an extremely hard balance to obtain. Factors such as catalyst structure, leaving group ability, nucleophilicity of the displacing group, solvents, agitation and temperature all contribute to the success of an efficient phase transfer system. For example, an increase in the temperature of a system is often accompanied by an increase in the reaction rate in the organic phase, but the disadvantage is the decomposition of the quaternary salt. For example, ammonium salts will decompose above 100 °C by either Hoffmann degradation or internal nucleophilic displacement as shown in Scheme 22.⁷⁰⁻⁷² This is sometimes overcome by the use of quaternary phosphonium salts which have higher temperature tolerances, however, these salts can be susceptible to basic conditions to yield phosphine oxides. Overall, the above demonstrates a number of variables, which can be changed or tuned in a reaction in order to optimise the conditions to obtain the required product.

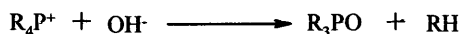
Decomposition by Hoffman degradation



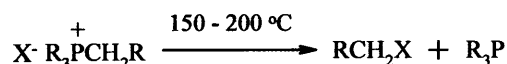
Decomposition by an internal displacement



Decomposition of phosphonium salt.

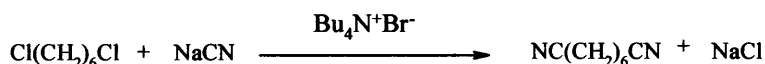


Decomposition by an internal displacement



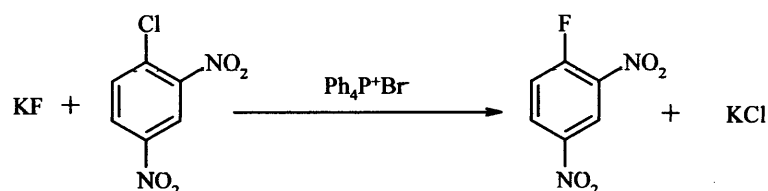
Scheme 22 Degradation of quaternary salts

A classic example of a displacement reaction is the cyanide displacement which has been used on a number of alkyl halides to yield nitriles as shown in Starks classic diagram (Scheme 21). Aqueous NaCN (liquid-liquid PTC) and simple tetraalkylammonium, usually containing butyl to decyl groups, or phosphonium salts give high yields of products at convenient temperatures between 75-110 °C. Tetrabutylammonium salts are usually a good choice for laboratory and industrial work since this salt can be easily removed by washing with water. Scheme 23 shows the conversion of 1, 6-dichlorohexane to suberonitrile, which is an important intermediate for the manufacturing of 1, 8-diaminooctane and of suberic acid, used in the production of Nylon-8.⁷³ Cyanide displacements can also be carried out using solid-liquid phase transfer systems provided a small amount of water is present. The initial introduction of water to the PT system allows the extraction of the PTC from the organic phase onto the surface of the salt. With highly active alkyl halides, such as benzyl halides, cyanide displacement can occur extremely fast to give alkylated phenylacetonitriles, however, byproducts can form. By slow addition of the NaCN to the reaction mixture, secondary products are avoided.



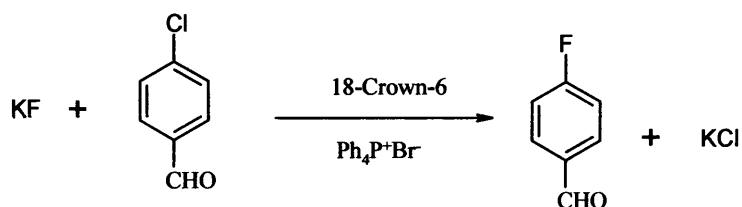
Scheme 23 Synthesis of suberonitrile

Other nucleophilic substitution reactions include halide displacement reactions which are reported to work well under phase transfer conditions. For example, the successful Halex reaction (Scheme 24) using tetraphenylphosphonium bromide has been reported.⁷⁴



Scheme 24 Halex reaction

It is known that the incorporation of electron withdrawing substituents such as nitro groups, activate the aromatic ring making substitution of the chloride ion easier. The inclusion of 18-crown-6 is considered to increase the solubility of KF in the solvent,^{75,76} as demonstrated by the reaction of chlorobenzaldehyde with Ph_4PBr and 18-crown-6 giving increased activity and yields compared to the phosphonium salt alone (Scheme 25). This particular reaction is usually difficult since the low activation of the aldehyde group does not help to promote the substitution of the fluoride ion. Polymer supported phase transfer catalysts for use in the Halex reaction have also been used allowing easy reaction and recycling.

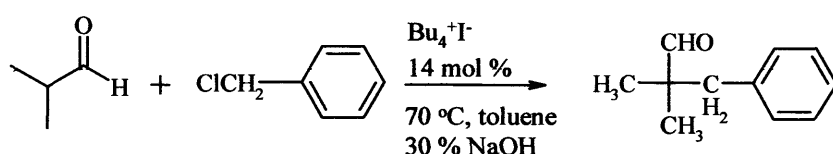


Scheme 25 Halex reaction of 4-chlorobenzaldehyde.

1.8 Phase Transfer Catalysed Reactions with Strong Bases

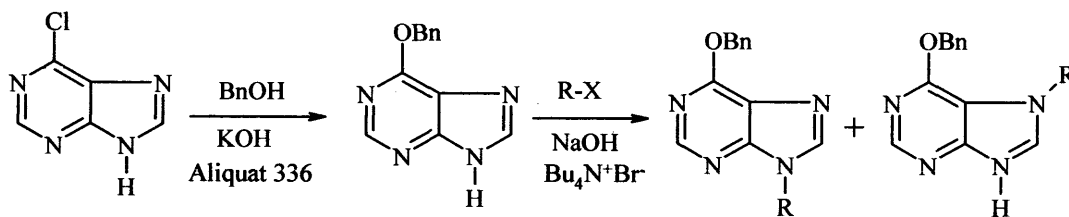
Although hydroxide ions can be used for displacement reactions, their full potential in PTC is seen through reactions such as the formation of ketones, aldehydes, esters, imines, nitriles, sulfones and hydrocarbons. The list is endless and a large amount of literature is directed towards this area. Several examples will be discussed below.

The C-H group α to a carbonyl group has a pK_a of around 20. Therefore, ketones and aldehydes do not require any special activation and should be readily deprotonated under PTC/ OH^- conditions. One example is the aldehyde, isobutyraldehyde, which can be alkylated by benzyl chloride in the presence of 14 mol% of TBAI and 30 % NaOH in toluene at 70 °C to yield 96 % of the monobenzylated isobutyraldehyde without aldol side products (Scheme 26).⁷⁷ Using the iodide anion in the phase transfer catalyst as a co-catalyst converts the benzyl chloride to benzyl iodide, thereby making a more active leaving group.



Scheme 26 Alkylation of hindered aldehyde

C, O, S and N-alkylation are important processes for the production of fine chemicals for the pharmaceutical and agrochemical industries. N-alkylation reactions have been applied to a number of heterocyclic compounds such as pyrazole to form N-alkyl pyrazoles in 91 – 98 % yields under solid-liquid conditions. Either the alkyl bromide or alkyl iodide can be used with TBAB and finely ground KOH with no evidence of catalyst poisoning from the iodide. Purines can also be N-alkylated under PTC conditions as shown in Scheme 27, in which the 6-chloro-9H-purine is reacted with BnOH to yield 6-benzyloxy-9H-purine. The product can then be N-alkylated under PT conditions to obtain N7-alkylated-6-benzyloxy-9H-purine and N9-alkylated-6-benzyloxy-9H-purine.⁷⁸



Scheme 27 N-Alkylation of purine

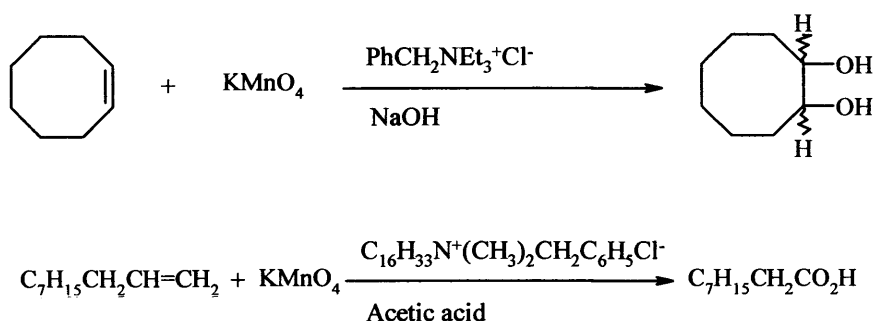
1.9 Phase Transfer Catalysed Oxidation Reactions

A number of oxidation reactions can be carried out using inexpensive oxidants such as potassium permanganate, sodium hypochlorite, hydrogen peroxide, oxygen, periodic acid and many others. Many oxidation reactions will require the use of a metal co-catalyst such as tungsten or a molybdenum based catalyst.

Potassium permanganate oxidations, under conventional methods, are limited due to potassium permanganates inability to dissolve in some solvents and on some occasions oxidation of the solvent can result. Another problem associated with these reactions is the precipitation of manganese dioxide as this can complicate the work up of the reaction.

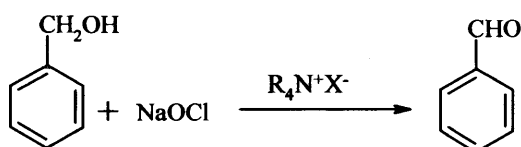
The permanganate anion is one of the easiest anions to transfer to the organic phase under phase transfer conditions with a variety of quaternary ammonium salts, phosphonium salts, crown ethers and cryptands. Quaternary ammonium and phosphonium permanganates can be easily prepared by the reaction of the quaternary ammonium chloride salt in an organic solvent and aqueous potassium permanganate solution. However, care must be taken since these quaternary ammonium permanganates undergo thermal decomposition and should be treated with caution.

A number of oxidation reactions have been carried out on olefins to form *cis*-diols, α -hydroxycarbonyls, carboxylic acids and aldehydes. However, the formation of products listed depends almost entirely on the reaction conditions and work up. The products obtained are dependent on the *pH* of the aqueous phase. For example, under basic conditions *cis*-diols (Scheme 28) are the major products,^{78,80} whilst under acidic conditions using acetic acid, carboxylic acids are formed. Liquid-liquid systems are not the only way to carry out permanganate reactions, solid-liquid systems may also be used, and polyethers are usually the catalyst of choice.

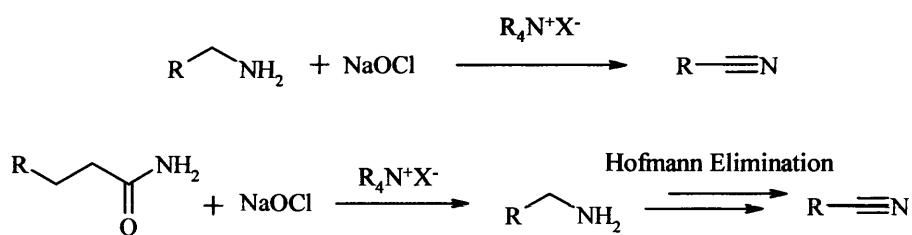


Scheme 28 Oxidation using KMnO_4 under basic and acidic conditions.

Lee and Freedman showed the potential for oxidising benzylic and secondary aliphatic alcohols to the corresponding carbonyl compounds using NaOCl .⁸¹ (Scheme 21). Aliphatic alcohols were found to oxidise slowly to the corresponding aldehydes and thereafter to the carboxylic acid. NaOCl has also been used for the oxidation of primary amines to give the nitrile compounds. The oxidation of amides gives the amine, however, successive Hofmann rearrangements result in the nitrile being formed (Scheme 30).



Scheme 29 Oxidation of benzyl alcohol using NaOCl



Scheme 30 Oxidation of amines and amides using NaOCl

The epoxidation of olefins carried out with NaOCl and quaternary ammonium salts results in little or no epoxidation product. However, if the oxidation is carried out using tetraphenylporphyrins, TPP, with a chelated metal such as manganese with aqueous NaOCl then good yields are obtained.⁸²⁻⁸⁶ By incorporating a large axial ligand such as 4-methylpyridine into the TPP framework, catalytic activity is increased; this is best

demonstrated by the epoxidation of propylene with 100 % selectivity and 80 % conversion (Figure 11). By adding large axial ligands to the tetraphenylporphyrin framework, this reduces the oxidative degradation of the porphyrin.⁸⁷ One drawback of using TPP complexes is the difficulty in synthesizing the porphyrins in substantial yields.

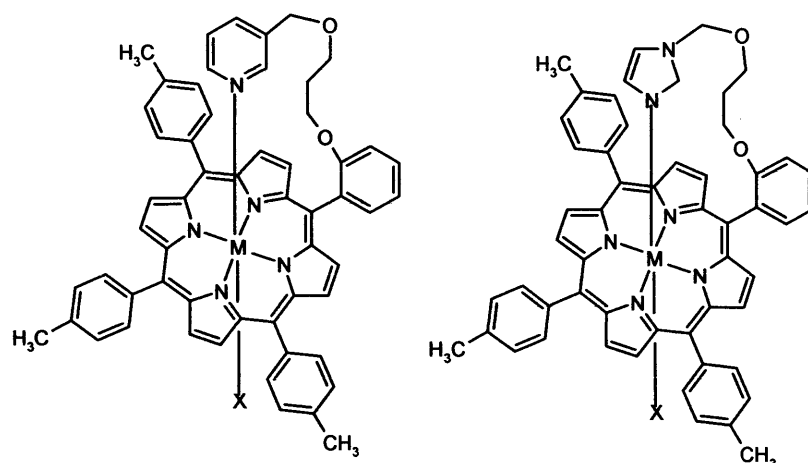


Figure 11 TPP derivatised catalysts for epoxidation reactions of olefins

1.10 Applications of Phase Transfer Catalysis in Industry

Phase transfer catalysis is widely used in industry for a number of advantages. These include high yields, increased reaction rates, milder reaction conditions, ability to use NaOH compared to other expensive bases and the use of a wide range of solvents. The advantages show a proven technology which is simple and easy to use with the ability of process optimisation. Although few, there are disadvantages which include product/catalyst separation, decomposition of quaternary ammonium and phosphonium salts, toxicity of catalysts such as crown ethers and cryptands and finally, recovery of catalyst usually results in the catalyst being discarded.

In industry, multistep reactions are referred to as cascade reactions and are fairly common in industry. In cascade reactions, several multireactions are carried out but no immediate separation is undertaken, instead reactions are carried out in a number of reactors which contain the appropriate reaction conditions. One example includes the reagent benzyl chloride which has a variety of industrially important products (Figure 12).⁸⁸ A number of key quaternary ammonium and phosphonium salts can be synthesised whilst benzylium

chloride (*N*-benzyl-*N,N*-dimethyl-*N*-alkylammonium chloride) are used for antiseptics and germicides. The conversion of BnCl into BnCN is a key commercial route for the synthesis of β -phenylalanine and phenylacetic acid. The conversion of BnCl to BnOH finds a number of applications in the fragrance industry and flavour industry. Dibenzyl ether is a side product formed from the hydrolysis of BnCl but can be obtained as the only product by manipulating the conditions of the experiment. The reaction of BnCl with NaS gives the dibenzylsulfide which is oxidised with dilute nitric acid to give $(C_6H_5CH_2)_2SO$ to be used as a corrosive inhibitor during metallic surface cleaning. C-alkylation of BnCl with isobutanal yields 2,2-dimethyl-3-phenylpropanal, which is a common perfumery compound, no poisoning is seen through the use of Bu_4NI and it is thought that BnCl is first converted to the iodide *in situ* to make a more reactive leaving group.

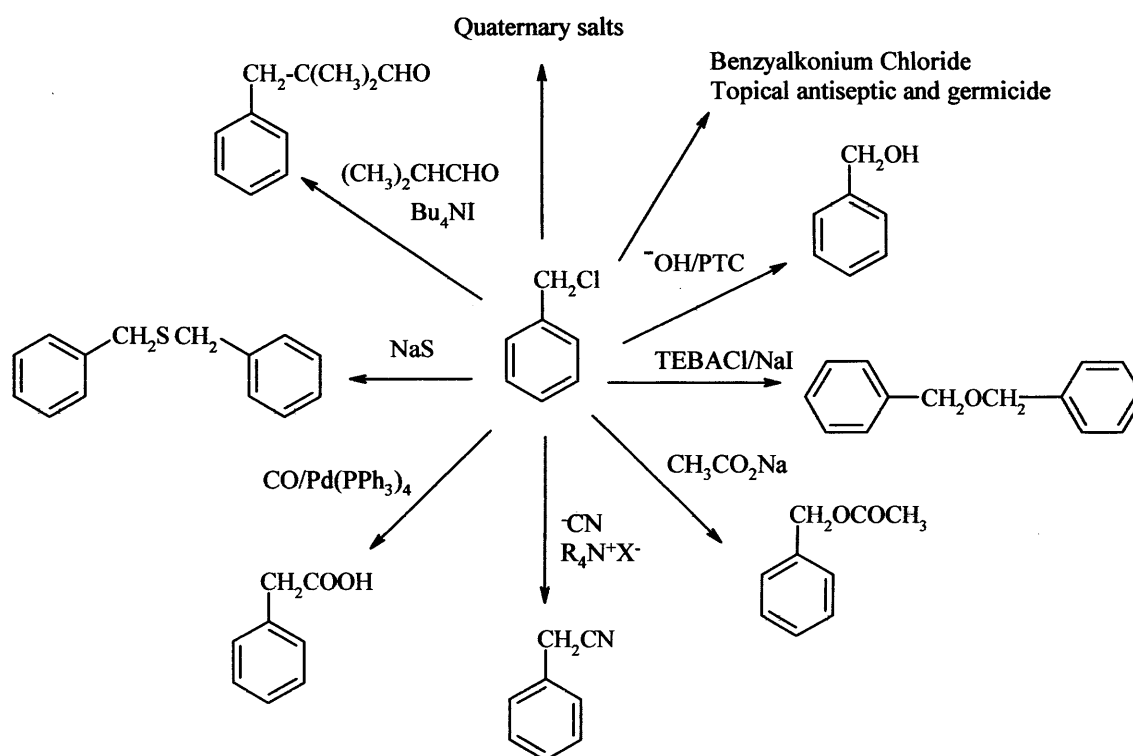


Figure 12 Industrial applications of BnCl under PTC

1.11 Separation and Triphase Catalysis

Separation of the phase transfer catalyst from the reaction mixture can be achieved by extraction, distillation and adsorption. Extractive methods need an additional solvent which can be distilled off to recover the catalyst. Distillation becomes increasingly

difficult and only feasible if the catalyst has a lower boiling point compared to the products and solvent used. However, the phase transfer catalyst which is recovered from the distillation residue can sometimes be contaminated with byproducts and other residual materials. By using a quaternary ammonium salt at temperatures above 100-120 °C, decomposition to the trialkylamine can be achieved and it can then be removed by the addition of dilute acid. In view of the fact that ammonium and phosphonium salts are inexpensive and used in low concentrations, the catalyst is not normally recovered but instead disposed of with copious amounts of water. Since separation of the product and the phase transfer catalyst can be difficult, investigation into separation methods has been reported. Such types of separation include absorption on ion exchange resins⁸⁹ or silica gel⁹⁰ but this adds cost to the process.

The applications of insoluble catalysts have been reported and involve the use of a resin bound catalyst or a *third phase* catalyst as shown in Figure 13. Obviously, the major advantage of insoluble phase transfer catalysts is the easy removal and recovery of the catalyst by filtration, but only 5-10 % of the industrial phase transfer catalysed reactions use insoluble phase transfer catalysts and the main problem is that most reactions are much slower with insoluble phase transfer catalysts compared to using conventional soluble phase transfer catalysts. A spacer group is normally present in the catalyst to protect the active function (attached quaternary salts) from the resin back bone, which causes an electron withdrawing effect. These spacer groups can range from 8-20 carbons in length and not only protect the active sites, but they are also beneficial for separating the ionic reaction centres from each other, reducing aggregation of functional groups.⁹¹ The basic polymer support is a styrene-divinylbenzene resin (SDV) which can be functionalised by chloromethylation or chlorination. The supported quaternary salts are thus obtained by the reaction of a tertiary amine or a phosphine.⁹² Macrocylic units such as crown ethers usually contain a hydroxyl or amine functionality. Reactions carried out under triphasic conditions are best exemplified by the reaction between 1-bromooctane and aqueous sodium cyanide and the butylation of phenylacetonitrile which both use the polymer supported tributylphosphonium catalyst (Scheme 31 and 32).

There are six steps which are required for triphasic catalysis to occur: 1) diffusion of aqueous sodium cyanide through to the resin bulk to the active sites, 2) exchange of CN⁻ for

Br^- at the active sites, 3) diffusion of Br^- out of the catalyst into the aqueous phase, 4) diffusion of the R-Br through the bulk resin to active sites, 5) chemical reaction, 6) diffusion of RCN out of the catalyst into the organic phase.

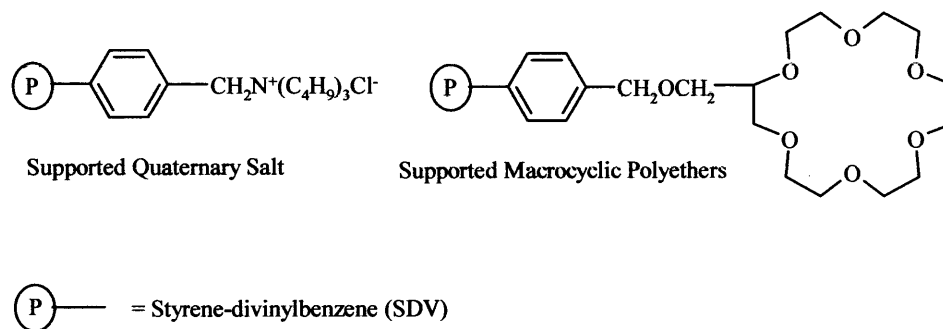
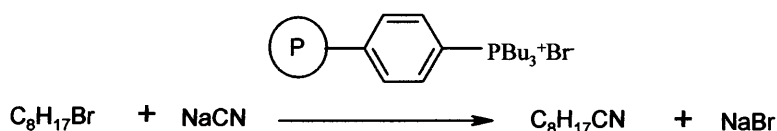
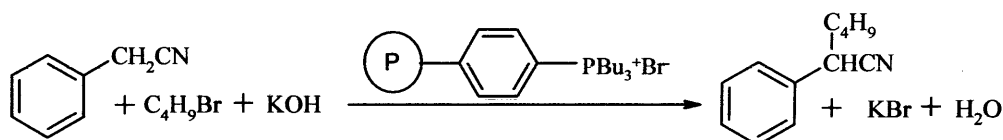


Figure 13 Examples of triphase catalysts.



Scheme 31 Triphase reaction between 1-bromooctane, sodium cyanide and polymer bound catalyst.



Scheme 32 Butylation of phenylacetonitrile using a polymer bound catalyst.

1.12 Outline of Research

The aim of the project is to synthesise a series of fluororous-tagged phosphonium phase transfer catalysts (Figure 14) which will provide improved separation and recycling compared to traditional methods. Separation using liquid-liquid extraction as well as separation by FRP silica gel will be investigated. By carrying out liquid-liquid extractions

between organic solvents and perfluorocarbon solvents the partition coefficients will be ascertained.

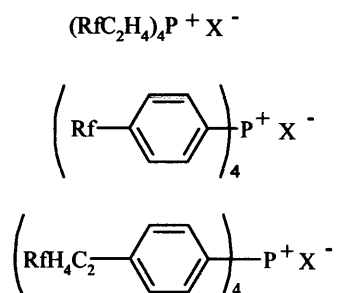


Figure 14 Phosphonium salts

Picrate extractions will be carried out to understand the effectiveness of the fluorous-tagged phosphonium salts at anion transfer. The application of the fluorous-tagged phosphonium salts will be used as phase transfer catalysts in halide exchange reactions under liquid-liquid and solid-liquid conditions and the conversion of products will be monitored by GC. Separation and recovery of the fluorous-tagged phosphonium salts will also be investigated. All of these areas will be compared directly against several commonly used non-fluorinated phase transfer catalysts such as $\text{PhCH}_2\text{-PPh}_3^+\text{Br}^-$, THAB, $\text{Bu-PPh}_3^+\text{Br}^-$.

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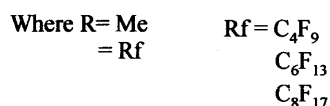
Chapter Two



2.0 First Generation Fluorous-Tagged Phosphonium Salts.

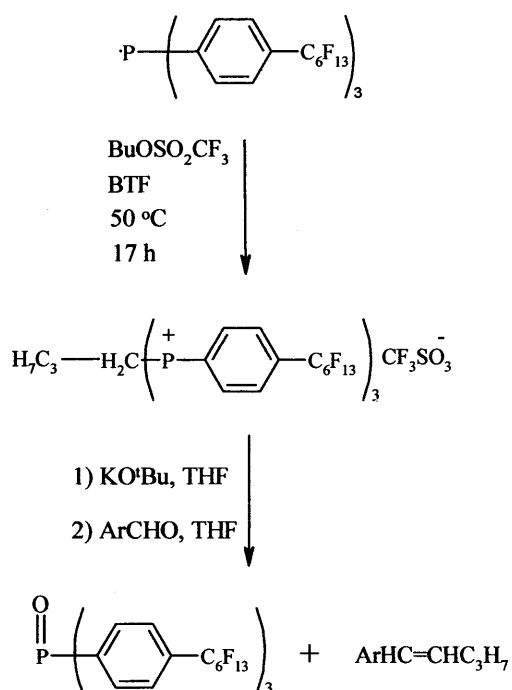
2.1 Introduction.

Very little work on the synthesis and applications of perfluorinated phosphonium salts is reported in the literature. The main development was by Sakakura who has reported the synthesis of perfluoroalkyl phosphonium iodides and investigated their application in catalysing propylene carbonate synthesis from propylene oxide and carbon dioxide under supercritical carbon dioxide conditions.¹ The group synthesised a number of novel perfluoroalkyl phosphonium salts (Scheme 33) in good yield (60 %) by reacting the tris(polyfluoroalkyl)phosphines with either methyl iodide or the corresponding perfluoroalkyl iodide in acetone. The perfluorinated phosphonium salts were shown to have similar reactivity and selectivity compared to the standard phase transfer catalyst, tetrabutylphosphonium iodide, in the cycloaddition reactions of CO₂ to propylene oxide.



Scheme 33 Synthesis of perfluorinated phosphonium salts

Work at the University of Leicester has been carried out on the synthesis of a butyl triaryl phosphonium salt (Scheme 34) for its use in the Wittig reaction.² The attachment of fluorous ponytails enables purification of the desired alkene to be easier and the removal of the triarylphosphine oxide can be accomplished by either liquid-liquid extraction between acetonitrile and perfluoro-1,3-dimethylcyclohexane or solid phase extraction using fluorous reverse phase silica gel.



Scheme 34 Formation of perfluorinated Wittig reagent

The aim of this chapter is to prepare a series of novel fluorous-tagged trialkyl and triaryl phosphonium salts by a simple quaternisation process (Figure 15). The fluorous-tagged phosphonium salts will be fully characterised by ^1H , ^{19}F , ^{31}P , and $^{13}\text{C}\{^1\text{H}\}$ NMR spectroscopy as well as mass spectroscopy and elemental analysis. Partition coefficients will be investigated between a perfluorocarbon solvent (PP3 or PFOB) and an organic solvent to evaluate their separation by liquid-liquid extraction. Solid phase extraction using FRP silica gel will also be ascertained. The results obtained from both liquid-liquid extractions and SPE over FRP silica gel will be compared directly so that the best route for separating and recovering the fluorous-tagged phosphonium salts is established.

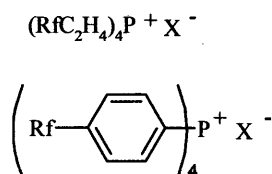


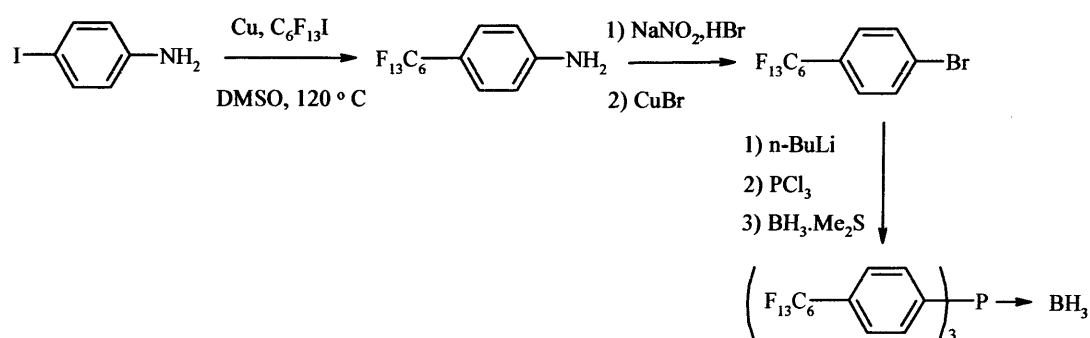
Figure 15

2.2 Literature Methods for the Preparation of Tris(4-perfluorohexylphenyl)

Phosphine.

Tris(4-perfluorohexylphenyl)phosphine, $P(4-C_6H_4C_6F_{13})_3$, was the first fluorous-soluble analogue of triphenylphosphine, PPh_3 , to be synthesised. The key step in its synthesis is the copper coupling methodology which is used to attach the perfluoroalkyl groups directly onto the aromatic ring. This method was originally developed by McLoughlin and Thrower in 1969³ and was improved further by Chen *et al.*^{4,5,6} Two independent groups reported the synthesis of the fluorous-derivatised triarylphosphine in 1997.^{7,8}

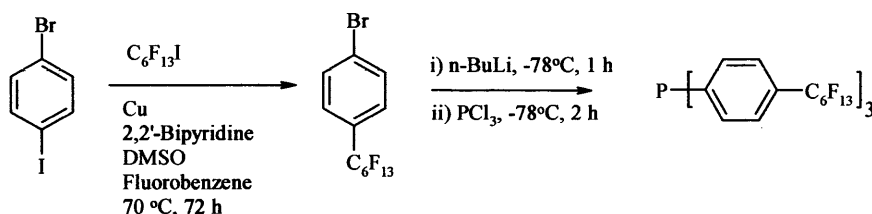
Knochel prepared the triarylphosphine, $P(4-C_6H_4C_6F_{13})_3$, in order to synthesise a fluorous Pd catalyst for the cross coupling of organo-zinc bromides with aryl iodides in the fluorous biphasic system. The synthetic route for the preparation of $P(4-C_6H_4C_6F_{13})_3$ is outlined in Scheme 35.⁷ The first step is the attachment of the perfluoroalkyl group to 4-iodoaniline to give the perfluoroalkylated aniline substrate in 86 % yield. A Sandmeyer reaction was then performed to obtain 4-bromo(perfluorohexyl)benzene. After reacting the 4-bromo(perfluorohexyl)benzene with butyl lithium, the aryllithiate was reacted with PCl_3 to form the phosphine, $P(4-C_6H_4C_6F_{13})_3$, which was protected to form a phosphane-borane complex. After purification the borane can be removed by reaction with diethylamine.



Scheme 35 Synthesis of triarylphosphine by the diazotisation route

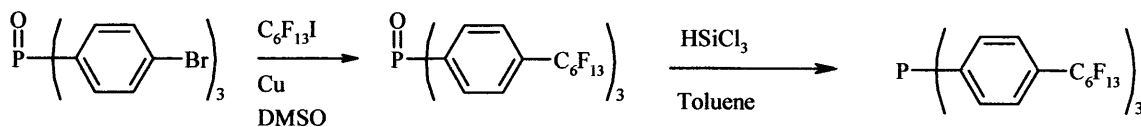
Hope *et al.* also reported the synthesis of the same triarylphosphine, $P(4-C_6H_4C_6F_{13})_3$, in 1997 using a very similar route.⁸ Scheme 36 shows that 4-bromo(perfluorohexyl)benzene was prepared in one step by a selective copper coupling reaction between 4-

bromiodobenzene and perfluorohexyl iodide. A bromine-lithium exchange using butyllithium was carried out to form the aryllithiate intermediate which was then reacted with PCl_3 to give tris(4-perfluorohexylphenyl)phosphine.



Scheme 36 Synthesis of tris(4-tridecafluorohexylphenyl)phosphine

In 2000 Xiao *et al.* developed an alternative high yielding synthesis of the triarylphosphine, $\text{P}(\text{4-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3$, which is shown in Scheme 37.⁹ The triarylphosphine oxide is easily made from the starting materials, 1,4-dibromobenzene and phosphorus trichloride using established procedures.¹⁰ To begin with, tris(4-bromophenyl)phosphine oxide underwent a copper coupling reaction with perfluorohexyl iodide to form the tris(4-perfluorohexylphenyl)phosphine oxide in high yields. This compound was then reduced with trichlorosilane to form the perfluoroalkylated triarylphosphine. Xiao developed this method further by incorporating the use of longer perfluoroalkylated chains in the triarylphosphine. Solubility problems are often associated with an increase in the length of the perfluoroalkyl chain, and when tris(4-perfluorooctylphenyl)phosphine was synthesised using the method shown in Scheme 36, a yield of only 26 % was obtained.¹¹ This can be accounted for by the low solubility of the perfluoroalkylated bromobenzene in ether at -78°C . However, the method described by Xiao allows the introduction of longer perfluoroalkyl groups and tris(4-perfluorooctylphenyl)phosphine was obtained in 93 % yield.



Scheme 37 Synthesis of fluoroalkylated arylphosphines by Cu-mediated cross coupling followed by reduction with trichlorosilane

2.3 Synthesis of Tris(4-perfluorohexylphenyl)phosphine.

Tris(4-perfluorohexylphenyl)phosphine was synthesised using the route shown in Scheme 36 that was developed at the University of Leicester.⁸ The first step is the selective copper coupling reaction between 1,4-bromoiodobenzene and perfluoro-*n*-hexyl iodide. The key to success is careful temperature control and slow addition of perfluoro-*n*-hexyl iodide, whereby the aryl iodide undergoes substitution more easily than the aryl bromide. However, the 4-bromo(perfluorohexyl)benzene was always contaminated with 4-iodo(perfluorohexyl)benzene and 1, 4-bis(perfluorohexyl)benzene as depicted in Figure 16. The 1,4-bis(perfluorohexyl)benzene product was easily removed by distillation, whilst the presence of the 4-iodoperfluorohexylbenzene did not pose any problems.

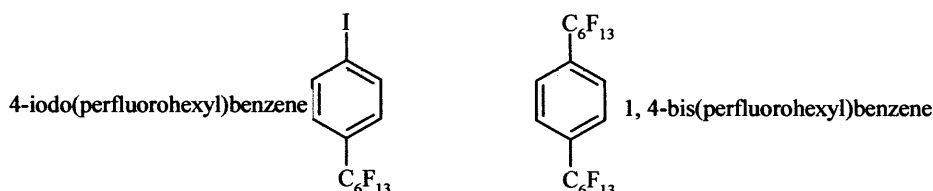


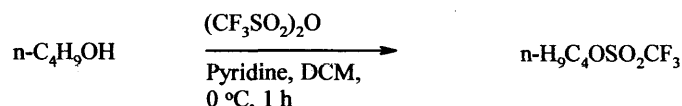
Figure 16 Side products formed during the copper coupling reaction

The next step is bromine-lithium exchange and the subsequent reaction with PCl_3 (Scheme 36). The addition of *n*-BuLi was carried out at -78°C , but as soon as the butyllithium was added, the reaction mixture was allowed to warm to -50°C to ensure complete lithiation before the addition of PCl_3 at -78°C . The crude phosphine, $\text{P}(4\text{-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3$ was distilled under reduced pressure to remove any traces of starting material and 1,4-bis(perfluorohexyl)benzene that still remained from the copper coupling reaction. Occasionally, the presence of the butyl phosphine, $\text{C}_4\text{H}_9\text{-P}(4\text{-C}_6\text{H}_4\text{C}_6\text{F}_{13})_2$ was observed and was formed by adding too much *n*-BuLi; the butyl phosphine can be seen in the ^{31}P NMR spectrum (δ_{P} -17 ppm). The butyl phosphine can be removed by washing in hexane and filtering to leave the triarylphosphine as a white solid, however, this is at the risk of oxidising the triarylphosphine, $\text{P}(4\text{-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3$ to triarylphosphine oxide $\text{P}(\text{O})(4\text{-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3$.

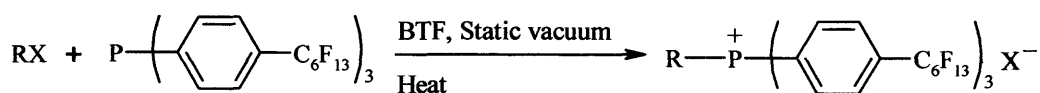
2.4 Synthesis of Perfluorinated Triaryl Phosphonium Salts.

Table 2 summarises the synthesis of a series of perfluoroalkylated triarylphosphonium salts by the quaternisation of the triarylphosphine, $P(4-C_6H_4C_6F_{13})_3$, as shown in Scheme 38. Previous work had shown that the reaction of the triarylphosphine with butyl bromide in benzotrifluoride at 110 °C resulted in only 6 % conversion after 5.5 days.¹² Only a low conversion was observed because of the electron withdrawing effects of the perfluoroalkyl group that reduces the nucleophilicity of the triarylphosphine. By providing a better leaving group such as the triflate, the conversion to the butyl triarylphosphonium salt was increased dramatically and approximately 60% conversion was obtained in 24 h.

The butyl trifluoromethanesulfonate was synthesised as shown in Scheme 39 when dried butanol was reacted with triflic anhydride using pyridine as the base. This butyl triflate was purified by distillation under reduced pressure at 30 mbar. It must be freshly prepared and kept in the fridge prior to use in order to prolong its shelf life, since if it is kept at room temperature it was found to decompose.



Scheme 39 Synthesis of butyl trifluoromethanesulfonate

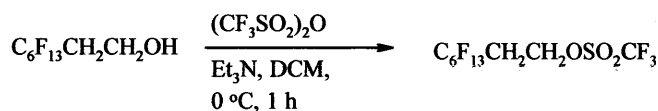


Scheme 38 Quaternisation reaction

R group	X ⁻ , anion	Temp (°C)	Time (h)	Yield (%)
C ₄ H ₉	Br	110	132	6
C ₄ H ₉	CF ₃ SO ₃	45	67	78
C ₆ F ₁₃ C ₂ H ₄	CF ₃ SO ₃	84	96	50
PhCH ₂	Br	100	32	70

Table 2 Synthesis of perfluorinated triaryl phosphonium salts using $P(4-C_6H_4C_6F_{13})_3$

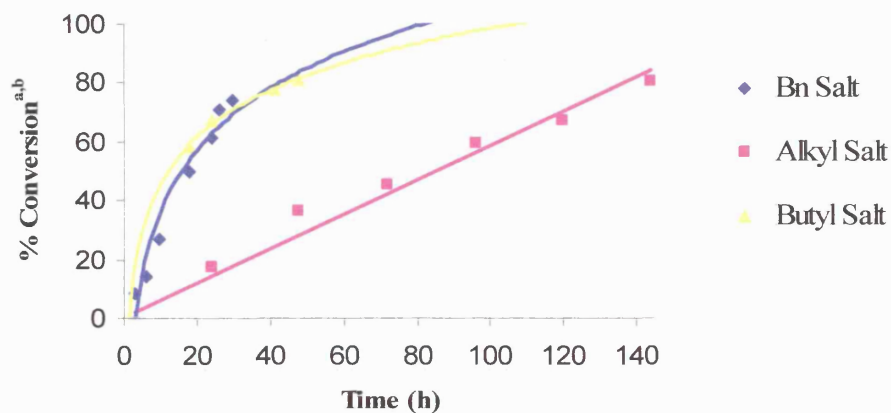
Two other salts were synthesised and these include the triaryl phosphonium salt which contains four fluororous ponytails and the benzyl triaryl phosphonium salt. The four fluororous ponytailed phosphonium salt was synthesised by reacting the triarylphosphine with 1*H*,1*H*,2*H*,2*H*-perfluorooctyltriflate. The triflate was synthesised by the reaction of 1*H*,1*H*,2*H*,2*H*-perfluorooctan-1-ol with triflic anhydride using triethylamine as the base (Scheme 40). A fluororous extraction between dichloromethane and PP3 was used to extract the fluororous product, 1*H*,1*H*,2*H*,2*H*-perfluorooctyl trifluoromethanesulfonate, in >70% yields. Benzylbromide was also used to form the benzyl phosphonium salt. A three fold excess of benzylbromide gave the desired product in 70 % yield.



Scheme 40 Synthesis of 1*H*,1*H*,2*H*,2*H*-perfluorooctyl trifluoromethane sulfonate

The formation of the triarylphosphonium salts were monitored by ³¹P NMR spectroscopy and the results are summarised in Figure 17. The conversion of the triarylphosphine to the benzyl and butyl triarylphosphonium salts are clean reactions with high conversion after 30 and 48 hours respectively. However, the rate of formation of the four fluororous ponytailed phosphonium salts was much slower giving 78 % conversion after 140 hours and so monitoring was reduced to 24 hour intervals. The benzyl salt was also synthesised using microwave conditions. The reaction time was successfully reduced from 30 hours to 15 minutes using a 10 fold excess of benzyl bromide. Removal of the benzylbromide, however, required several washes with hexane and one final wash with diethyl ether.

**% Conversion of Fluorous-Tagged Phosphonium
Salts by $^{31}\text{P}\{^1\text{H}\}$ NMR**



^a $^{31}\text{P}\{^1\text{H}\}$ NMR integration of salt : triarylphosphine oxide : triarylphosphine

^b In all the reactions that were monitored, approximately 7 % of the reaction mixture was triarylphosphine oxide.

Figure 17 Synthesis of perfluoro-tagged phosphonium salts
(monitored by ^{31}P NMR spectroscopy)

As expected, the ^{31}P NMR signals of the fluorous-tagged phosphonium salts were shifted downfield (δ_{P} 25.3 – 27.0 ppm) (Table 3). The $^{13}\text{C}\{^1\text{H}\}$ NMR spectra showed that the phosphorus carbon (PC) signals were coupled to phosphorus (δ_{C} 122.4-122.8, $^1J_{\text{CP}} = 84.8 - 86.5$ Hz), whilst the ArCHCF_2 signals were coupled to fluorine (δ_{C} 134.3 – 134.9, $^2J_{\text{CF}} = 23.3 - 24.6$ Hz) and only the benzyl triaryl phosphonium salt coupled to the phosphorus ($^4J_{\text{CP}}$ 3.9 Hz) as well. The mass spectra proved to be invaluable throughout the work as it showed peaks for both the cations and anions. Elemental analysis demonstrates that all the phosphonium salts were obtained in analytically pure forms.

F-Salt	δ_P (ppm)	CP δ_C (ppm) shifts and Coupling Constants.	ArCH₂CF₂ δ_C (ppm) shifts and Coupling Constants
PhCH ₂ P(ArRf) ₃	25.3	122.8 (d, $^1J_{CP}$ = 84.8 Hz)	134.3 (td, $^2J_{CF}$ = 24.6 Hz, $^4J_{CP}$ 3.9 Hz)
Bu-P(ArRf) ₃	26.0	122.8 (d, $^1J_{CP}$ = 85.0 Hz)	134.6 (t, $^2J_{CF}$ = 23.3 Hz)
RfC ₂ H ₄ -P(ArRf) ₃	27.0	122.4 (d, $^1J_{CP}$ = 86.5 Hz)	134.9 (t, $^2J_{CF}$ = 24.1 Hz)

Table 3 NMR data of the perfluorinated phosphonium salts

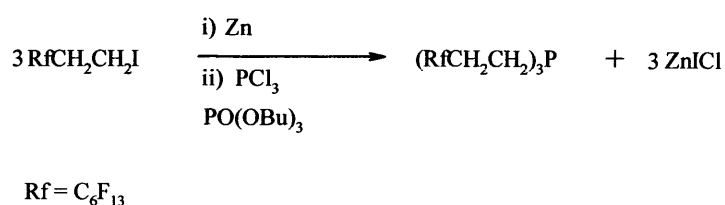
Table 4 shows the melting points of the fluorous-tagged phosphonium salts and several analogous phase transfer catalysts. Firstly, it is clear to see that the melting point of the fluorous-tagged phosphonium salts are normally lower than their analogous non-fluorinated phosphonium salts. This is evidently seen by the comparison of PhCH₂-PPh₃⁺Br⁻ and PhCH₂-P(C₆H₄C₆F₁₃)₃⁺Br⁻ which have melting points of 295-298 °C and 139-141 °C respectively. The inclusion of the anion, CF₃SO₃⁻, also causes a decrease in melting points, and can be seen by comparing the butyltriphenylphosphonium bromide, Bu-PPh₃⁺Br⁻, which has a melting point of 240-243 °C with its analogous salt, Bu-PPh₃⁺CF₃SO₃⁻, which has a melting point of 99-100 °C. The introduction of the fluorous ponytails in the butyl salt further reduces the melting point temperature to 85-89 °C. A similar result is also observed when Bu-PPh₃⁺CF₃SO₃⁻ (99-100 °C) is compared with C₆F₁₃CH₂CH₂-PPh₃⁺CF₃SO₃⁻ (81-83 °C) but this is not the case for the heavily fluorinated phosphonium salt.

Phase Transfer Catalyst	Melting Point (°C)
$\text{PPh}_4^+\text{Br}^-$	295-298
$\text{PhCH}_2\text{-PPh}_3^+\text{Br}^-$	295-298
$\text{PhCH}_2\text{-P(C}_6\text{H}_4\text{C}_6\text{F}_{13})_3^+\text{Br}^-$	139-141
$\text{Bu-PPh}_3^+\text{Br}^-$	240-243
$\text{Bu-PPh}_3^+\text{CF}_3\text{SO}_3^-$	99-100
$\text{Bu-P(C}_6\text{H}_4\text{C}_6\text{F}_{13})_3^+\text{CF}_3\text{SO}_3^-$	85-89
$\text{C}_6\text{F}_{13}\text{C}_2\text{H}_4\text{-PPh}_3^+\text{CF}_3\text{SO}_3^-$	81-83
$\text{C}_6\text{F}_{13}\text{CH}_2\text{CH}_2\text{-P(C}_6\text{H}_4\text{C}_6\text{F}_{13})_3\text{CF}_3\text{SO}_3^-$	157-162

Table 4 Melting points of perfluorinated and non-fluorinated phosphonium salts

2.5 Literature Methods for the Preparation of Tris(1*H*,1*H*,2*H*,2*H* – perfluorooctyl)phosphine.

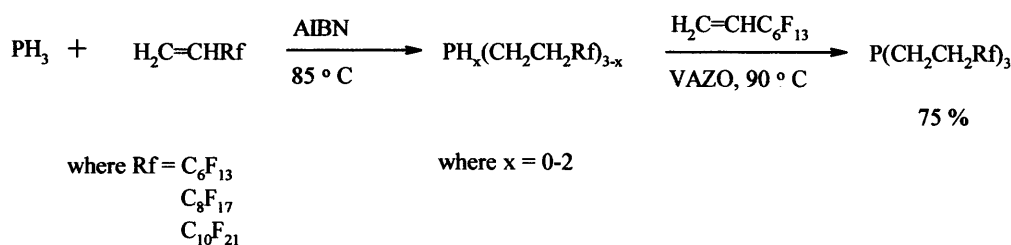
A substantial amount of research has been targeted at the preparation of fluorine-tagged phosphines for applications as ligands in fluorine biphasic catalysis. The first reported synthesis of the trialkylphosphine, $\text{P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3$, was in 1985 by Benéfic-Malouet *et al.* who used the organo-zinc methodology shown in Scheme 41.¹³



Scheme 41 Formation of tris(1*H*,1*H*,2*H*,2*H* – perfluorooctyl)phosphine using organo-zinc route

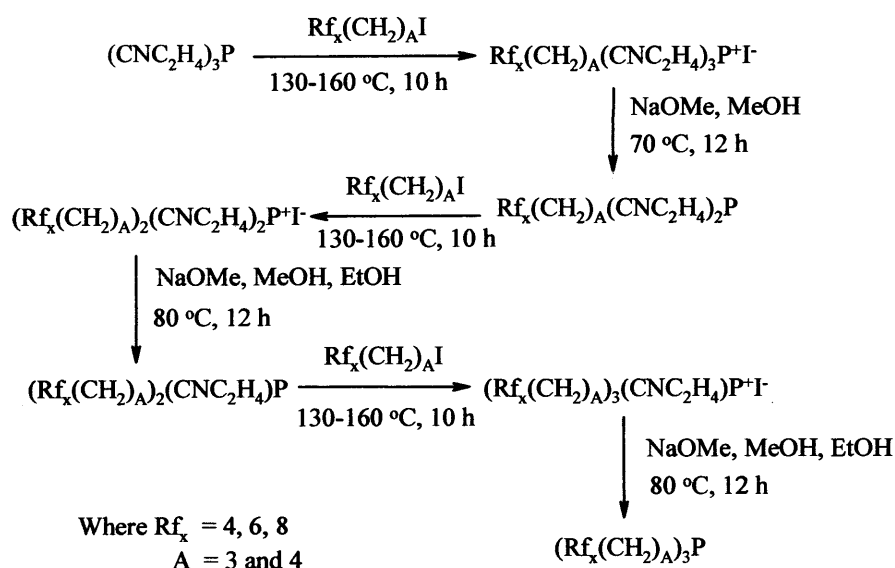
Horváth and Rábai later developed a radical addition reaction between PH_3 and 1*H*,1*H*,2*H*-perfluoro-1-octene.¹⁴ The synthesis was conducted in an autoclave at 100 °C in the presence of the radical initiator, AIBN. Unfortunately, a low yield of only 26 % was obtained. Gladysz later refined this method as shown in Scheme 42 and in order to

improve yields a $\text{PH}_3/\text{H}_2\text{C}=\text{CHRf}$ stoichiometry of 1:3 was always used, temperatures of 80 - 85 °C were used to avoid rapid decomposition of AIBN and the mixtures of primary and secondary phosphines obtained were sequentially treated with a secondary charge of the perfluoroalkene and the initiator VAZO.¹⁵ Longer perfluoroalkyl chains can also be incorporated into the same synthesis of $\text{P}(\text{CH}_2\text{CH}_2\text{C}_8\text{F}_{17})_3$ and $\text{P}(\text{CH}_2\text{CH}_2\text{C}_{10}\text{F}_{21})_3$ which were prepared in 70% and 63% yields respectively as shown in Scheme 42. In some cases the trialkylphosphine oxide, $\text{P}(\text{O})(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3$ is produced in the reaction, but it can be successfully reduced to the phosphine, $\text{P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3$, by using trichlorosilane (HSiCl_3).



Scheme 42 Synthesis of trialkylphosphines using Gladysz's method

More recently, Horváth *et al.* have carried out the modular synthesis of trialkyl phosphines which allows the control of the number of methylene spacers as well as the length of the fluororous ponytails (Scheme 43).¹⁶ The synthesis involves the alkylation of 2-cyanoethyl substituted phosphines with $\text{Rf}_x(\text{CH}_2)_A\text{I}$ (where $\text{Rf}_4 = \text{C}_4\text{F}_9$; $\text{Rf}_6 = \text{C}_6\text{F}_{13}$; $\text{Rf}_8 = \text{C}_8\text{F}_{17}$; $A = 3$ and 4; $X = 4, 6$ and 8). The perfluorinated alkyl iodide is used in 50 – 70 % excess allowing it to be used as a solvent and a reagent, thereby, giving the phosphonium iodide, $\text{Rf}_x(\text{CH}_2)_A(\text{CNCH}_2\text{CH}_2)_3\text{P}^+\text{I}^-$ in high yields, 98 – 99 %. Dealkylation of the 2-cyanoethyl group with sodium methoxide yields 2-methoxypropionitrile and the phosphine, $(\text{Rf}_x(\text{CH}_2)_A)_3\text{P}$. Yields of the trialkyl phosphines vary as shown in Table 5. Unfortunately, there are no reports for the synthesis of the trialkylphosphine with two methylene spacer units, $(\text{Rf}_6(\text{CH}_2)_2)_3\text{P}$ in this paper. Despite this, the route outlined in Scheme 43 shows a more viable preparation of trialkylphosphines with varying methylene spacer units and fluororous ponytails. One disadvantage is the large amounts of the perfluoroalkyl iodide required which incorporates an additional cost factor into the overall synthesis.

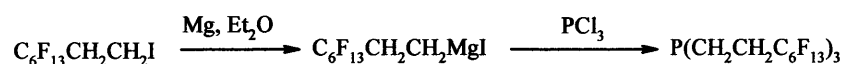


Scheme 43 Synthesis of trialkylphosphines using Horváth's method

Fluorous Phosphine	Yields (%)
$(\text{Rf}_4(\text{CH}_2)_3)_3\text{P}$	33.9
$(\text{Rf}_6(\text{CH}_2)_3)_3\text{P}$	46.2
$(\text{Rf}_8(\text{CH}_2)_3)_3\text{P}$	54.0
$(\text{Rf}_8(\text{CH}_2)_4)_3\text{P}$	52.5
$(\text{Rf}_8(\text{CH}_2)_3)(\text{Rf}_8(\text{CH}_2)_4)_2\text{P}$	52.9
$(\text{Rf}_6(\text{CH}_2)_3)(\text{Rf}_8(\text{CH}_2)_3)(\text{Rf}_8(\text{CH}_2)_4)\text{P}$	46.8

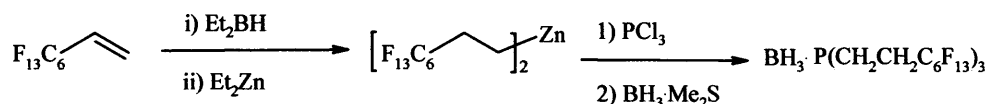
Table 5 Percentage yields of fluorous phosphonium salts.

An alternative method, developed at the University of Leicester, employs the Grignard reagent, which was prepared from 1*H*,1*H*,2*H*,2*H*-perfluorooctyl iodide as shown in Scheme 44.⁸ This Grignard intermediate can then undergo reaction with PCl_3 to give the phosphine in moderate yields of 50%. Holmes *et al.* have also used this methodology to synthesise fluorous-tagged phosphines which were used to prepare a series of Pd complexes as catalysts in both the Heck and Suzuki reactions in supercritical carbon dioxide.¹⁷



Scheme 44 Grignard route for the preparation of trialkylphosphine

The reinvestigation of the organo-zinc reagents by Knochel has also been reported.¹⁸ Knochel *et al.* have investigated the use of a diorganozinc compound which can be prepared from the reaction of an olefin via a hydroboration/boron-zinc exchange sequence, as shown in Scheme 45 and subsequently, these can be reacted with the required phosphorus chloride reagents (PCl_3 , PPhCl_2 , $\text{Cl}_2\text{P}(\text{CH}_2)_2\text{PCl}_2$) to give the required phosphines in 63-80 % yields.



Scheme 45 Preparation of polyfunctional phosphines using zinc organometallics

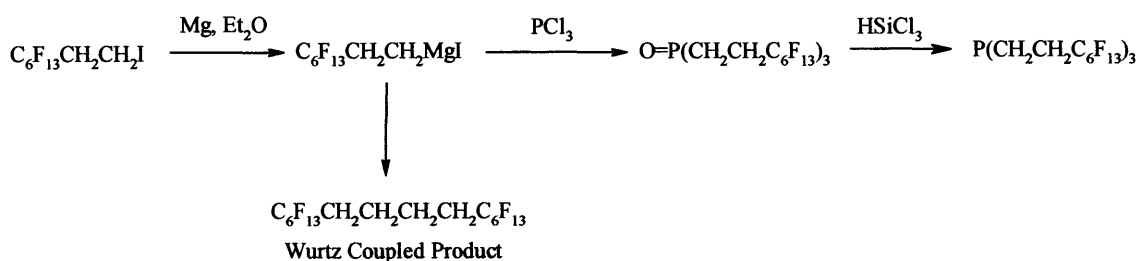
2.6 Synthesis of Tris(1*H*,1*H*,2*H*,2*H*-perfluorooctyl)phosphine.

In order to prepare tris(1*H*,1*H*,2*H*,2*H*-perfluorooctyl)phosphine, the Grignard reaction shown in Scheme 44 was employed. The advantage of this method is that it avoids the use of the extremely toxic PH_3 .

Initially, it was decided that an easier work up of the reaction mixture would be to carry it out in air in order to form the trialkylphosphine oxide, $\text{P}(\text{O})(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3$ (Scheme 46). The trialkylphosphine oxide, $\text{P}(\text{O})(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3$, could then be reduced using trichlorosilane to obtain the required trialkylphosphine. Although this route seemed easier in terms of work up and handling the air stable phosphine oxide, it proved to be extremely difficult with large amounts of inorganic salts and low yields of the trialkylphosphine oxide, $\text{P}(\text{O})(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3$ obtained. It was thus decided that the reaction should be carried out entirely under nitrogen.

In the first reaction it was thought that initiation problems prevented the formation of the Grignard reagent and so, it was refluxed overnight but large amounts of Wurtz coupled

product, $\text{C}_6\text{F}_{13}\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13}$, were formed. In order to overcome this problem, continuous entrainment with 1,2-dibromoethane was used by continuously adding the 1,2-dibromoethane along with the perfluorooctyl iodide to the magnesium. This meant that after the addition was complete the reflux duration was reduced to just two hours. After several attempts at this method, the work up under nitrogen was eventually successful. Any starting material and coupled product could be removed by distillation and pure trialkylphosphine, $\text{P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3$ was acquired in modest yields of 40%.



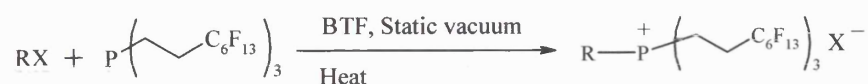
Scheme 46 Synthesis of Wurtz coupled product and
reduction of phosphine oxide

An alternative route for the preparation of tris(1*H*,1*H*,2*H*,2*H*-perfluorooctyl)phosphine using $\text{RfCH}_2\text{CH}_2\text{ZnI}$ was also investigated. Initially, the zinc dust was activated by reaction with 1,2-dibromoethane and TMSCl , before reacting with 1*H*,1*H*,2*H*,2*H*-perfluorooctyl iodide to form the perfluoroalkyl zinc intermediate. Addition of PCl_3 should result in the formation of the trialkylphosphine. Unfortunately, after obtaining the crude product, a number of peaks were found in the ^{31}P NMR spectrum with no indication of the required trialkylphosphine, $\text{P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3$.

2.7 Synthesis of Perfluorinated Trialkyl Phosphonium Salts.

A series of perfluoroalkylated phosphonium salts were synthesised by the quaternisation of the trialkylphosphine, $\text{P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3$, as shown in Scheme 47. Previous work¹² had shown that refluxing $\text{P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3$ with a 20 fold excess of butyl bromide in benzotrifluoride at 110 °C for 80 hours and then 115 °C for a further 90 hours resulted in no reaction. The quaternisation is an $\text{S}_{\text{N}}2$ reaction and requires a more activated leaving group since the nucleophilicity of the phosphine is reduced because of the electron

withdrawing effects of the fluoros ponytails (Table 6). The most versatile leaving group has proved to be the trifluoromethanesulfonate group.



Scheme 47 Quaternisation of trialkylphosphine

R group	X ⁻ , anion	Temp (°C)	Time (h)	Yield (%)
C ₄ H ₉	Br	115	170	0
C ₄ H ₉	CF ₃ SO ₃	45	48	65
C ₆ F ₁₃ C ₂ H ₄	CF ₃ SO ₃	80	37	41
PhCH ₂	Br	110	24	71

Table 6 Synthesis of perfluorinated alkyl phosphonium salts using P(CH₂CH₂C₆F₁₃)₃

Initially, the trialkylphosphine was refluxed with an excess of butyl trifluoromethanesulfonate for 40 hours. This first attempt was abandoned since the solution was heated too vigorously resulting in the decomposition of the butyl trifluoromethanesulfonate. After realising that the reaction was temperature sensitive, the experiment was repeated at a lower temperature of 45 °C. This proved very successful and the solvent was removed to give a viscous oil which was triturated with hexane and then with toluene. However, the salt was obtained as an extremely viscous oil and consequently, it could potentially be used as a fluoros ionic liquid.



The tetraalkyl phosphonium salt, [P(CH₂CH₂C₆F₁₃)₄]⁺CF₃SO₃⁻, was prepared by the reaction between the trialkylphosphine and 1*H*,1*H*,2*H*,2*H*-perfluorooctyl trifluoromethanesulfonate in a ratio of 1:4.8 in benzotrifluoride at 80 °C for 37 h. At the end of the reaction, the solvent was removed to leave an oil which was washed with hexane and toluene several times to remove any excess triflate and it eventually formed a solid type appearance. The salt was also placed

under vacuum at intervals in order to help it solidify resulting in the formation of a foam. The salt was washed for the last time with diethyl ether to remove any traces of phosphine oxide present in the system. Care is taken at this stage since some of the salts are slightly soluble in diethyl ether. The benzyl trialkyl perfluorinated phosphonium salt, $[\text{PhCH}_2\text{-P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3]^+\text{Br}^-$ was prepared by refluxing tris(1*H*,1*H*,2*H*,2*H*-perfluorooctyl)phosphine with an excess of benzyl bromide for 24 hours. The same work up procedure was used to purify the desired product to give a white powder in 71 % yield.

As expected the ^{31}P NMR signals of the fluorine-tagged phosphonium salts were shifted downfield (δ_{P} 36.9 – 42.4 ppm) (Table 7). The $^{13}\text{C}\{^1\text{H}\}$ NMR spectra showed that the PCH_2 signals were coupled to phosphorus (δ_{C} 10.6 – 11.2 ppm, $^1J_{\text{CP}} = 51.4 - 51.8$ Hz) but not to fluorine, whilst the CH_2CF_2 signals were coupled to fluorine (δ_{C} 23.4 – 23.7 ppm, $^2J_{\text{CF}} = 22.5$ Hz) but not to phosphorus. The mass spectra proved invaluable throughout the work as they showed peaks for both the cations and the anions. Elemental analysis demonstrated that all of the phosphonium salts were obtained in analytically pure form. The fluorine phosphonium salts melted in the range of room temperature to 84 °C showing the potential to be used as novel fluorine ionic liquids.

Salt	δ_{P} (ppm)	CP δ_{C} (ppm) shifts and Coupling Constants	ArCH ₂ CF ₂ δ_{C} (ppm) shifts and Coupling Constants
PhCH ₂ -P(C ₂ H ₄ Rf) ₃	36.9	11.2 (d, $^1J_{\text{CP}} = 51.4$ Hz)	23.7 (t, $^2J_{\text{CF}} = 22.4$ Hz)
Bu-P(C ₂ H ₄ Rf) ₃	40.0	10.6 (d, $^1J_{\text{CP}} = 51.8$ Hz)	23.4 (m)
RfC ₂ H ₄ -P(C ₂ H ₄ Rf) ₃	42.4	10.8 (d, $^1J_{\text{CP}} = 51.8$ Hz)	23.5 (t, $^2J_{\text{CF}} = 22.5$ Hz)

Table 7 NMR data of the perfluorinated phosphonium salts

2.8 Partition Coefficients.

Partition coefficients provide valuable data on the distribution of a solute between two immiscible phases and are extensively used throughout chemistry. To extract fluorous catalysts from reactions involving organic and fluorous solvents, partition coefficients for liquid-liquid biphasic systems must be determined. The measure of partition coefficients gives a direct measure of the fluorophilicity or fluorous phase affinity. Partition coefficients are normally expressed as ratios which have been normalised to 100 (e.g. 98.3:1.7), together with logarithmic values (Log P). Log P indicates a concentration ratio with the non-fluorous phase in the denominator. The natural logarithm of the perfluorocarbon phase/organic phase concentration ratio, $\text{Log} \{ [c(\text{perfluorocarbon})] / [c(\text{organic})] \}$ has been given the abbreviation f , for fluorophilicity.

Gladysz *et al.* have investigated a wide range of perfluorinated phosphines and determined their partition coefficients experimentally (Table 8).¹⁹⁻²¹ It is clear to see that as the length of the fluorous ponytails within the trialkylphosphine increases, the partition coefficients increase. Conversely, as the hydrocarbon spacer group increases, the partitioning of the phosphine in to the fluorous phase decreases.

Compound	Solvent System	Fluorous : Organic	Method
[Rf ₆ (CH ₂) ₂] ₃ P	CF ₃ C ₆ F ₁₁ /toluene	98.8 : 1.2	GLC
[Rf ₈ (CH ₂) ₂] ₃ P	CF ₃ C ₆ F ₁₁ /toluene	>99.7 : <0.3	GLC
[Rf ₁₀ (CH ₂) ₂] ₃ P	CF ₃ C ₆ F ₁₁ /toluene	>99.7 : <0.3	GLC
[Rf ₆ C ₆ H ₄] ₃ P	1,3-(CF ₃) ₂ C ₆ F ₁₀ /toluene	81 : 19	Gravimetric
[Rf ₆ (CH ₂) ₂ C ₆ H ₄] ₃ P	1,3-(CF ₃) ₂ C ₆ F ₁₀ /toluene	47 : 53	Gravimetric
[Rf ₆ (CH ₂) ₃ C ₆ H ₄] ₃ P	1,3-(CF ₃) ₂ C ₆ F ₁₀ /toluene	19.5 : 80.5	GLC

Table 8 Partition coefficients of perfluorinated phosphines.

Normally, the partition coefficients are analysed by GLC or HPLC which are the most reliable methods to use. However, for our purposes we chose to use gravimetric determinations. It is important to realise that the partition coefficients only give an indication of the fluorophilicity of the perfluorinated compounds because it is dependent on both the organic and the perfluorocarbon solvent used. More importantly, the partition coefficients will also change during a reaction because of the presence of the substrate and/or product as well as the presence of any reagents. Consequently, we chose to use a gravimetric method for determining partition coefficients because they will be different in each reaction that is tested depending on the substrate, product(s), reagent(s) and the solvent system used.

The gravimetric determinations involved accurately weighing out a known amount of the fluorous – tagged phosphonium salt and placing it in a sample vial containing an organic solvent (2 cm³) and a perfluorocarbon solvent (2 cm³), PP3. The phases were then stirred for 30 minutes and left to stand for an additional 30 minutes. A sample (1 cm³) of each solvent was removed, placed in a pre-weighed flask and concentrated down to dryness; to ensure complete dryness, the sample is placed under oil pump vacuum. All the partition coefficients are temperature dependent since the fluorous solute will have a stronger affinity for the fluorous phase at lower temperatures; all experiments were carried out between 22-25 °C. The weights obtained were then converted to partition coefficients (%) and Log P values. The information obtained will be used to decide whether separation by

liquid – liquid extraction is the best route or whether the use of FRP silica gel is the preferred method.

The first salt that was tested was the tetraalkyl salt, $[P(CH_2CH_2C_6F_{13})_4]^+CF_3SO_3^-$ (Table 9). It can be seen that the best solvent systems use either toluene or dichloromethane as the organic solvent and >95 % of the salt is anchored in the perfluorocarbon phase. On the other hand, the reverse is seen in the PP3/acetonitrile system.

Solvent System	Partition % ^a Fluorous:Organic	Log P = $C_{fluorous}/C_{organic}$
PP3 : Toluene	96.3 : 3.7	1.42
PP3 : DCM	96.2 : 3.8	1.40
PP3 : Chloroform	87.0 : 13.0	0.83
PP3 : MeOH	72.0 : 28.0	0.41
PP3 : Acetonitrile	19.7 : 80.3	-0.61

^a Average taken over three runs.

Table 9 Partition coefficients for $[P(CH_2CH_2C_6F_{13})_4]^+CF_3SO_3^-$

The benzyl trialkyl salt, $[PhCH_2P(CH_2CH_2C_6F_{13})_3]^+Br^-$ (Table 10) was tested in the solvent systems in which the tetraalkyl salt had been successful employed: toluene, dichloromethane (DCM) and methanol (MeOH). However, this salt was insoluble in some of the solvent systems such as PP3/DCM and PP3/toluene in which a cloudy white suspension was seen in both of the PP3 layers. These results demonstrated that the

accountability was low due to the heterogeneous nature of the system (Table 10). On the other hand, the MeOH system was colourless and no suspension was seen, though, the result obtained suggests that the salt preferred the organic layer (86 %) and a different perfluorocarbon solvent, perfluorooctyl bromide (PFOB) was investigated.

The organic solvents and PFOB are slightly miscible so standard measurements between toluene, DCM, MeOH, acetonitrile and PFOB were carried out so that this can be incorporated into the calculations of the partition coefficients (Table 11). The results show that good preferential solubility of the salt in the perfluorocarbon phase can be achieved when either toluene or DCM is used as the organic phase and good accountability of the salt was achieved (Table 12).

Solvent System	Partition % ^a Fluorous:Organic	Log P = $C_{\text{fluorous}}/C_{\text{organic}}$
PP3 : DCM ^b	93.7 : 6.3	1.20
PP3 : Toluene ^b	75.9 : 24.1	0.50
PP3 : MeOH	14.3 : 85.7	-0.78

^a Average of three runs.

^b Poor accountability of the fluorous phosphonium salt

Table 10 Partition coefficients for $[\text{PhCH}_2\text{-P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3]^+\text{Br}^-$

Solvent ^a	Measurements
PFOB	5.0 cm ³
Toluene	3.0 cm ³
PFOB	4.0 cm ³
Methanol	4.0 cm ³
PFOB	4.6 cm ³
DCM	3.4 cm ³
PFOB	4.0 cm ³
Acetonitrile	4.0 cm ³

^a 4 cm³ of each solvent was used in this experiment

Table 11 Organic and PFOB measurements

Solvent System	Partition % ^a Fluorous:Organic	Log P = C _{fluorous} /C _{organic}
PFOB:Toluene	96.5:3.5	1.44
PFOB:DCM	93.9:6.1	1.18
PFOB:MeOH	55.0:45.0	0.09
PFOB:Acetonitrile	13.0:87.0	-0.82

^a Average taken over three runs.

Table 12 Partition coefficients for [PhCH₂-P(CH₂CH₂C₆F₁₃)₃]⁺Br⁻

The next salt to be tested was the triaryl phosphonium salt containing four fluorous ponytails, [C₆F₁₃CH₂CH₂P(4-C₆H₄C₆F₁₃)₃]⁺CF₃SO₃⁻ (Table 13) giving a direct comparison against the tetraalkyl salt, P(CH₂CH₂C₆F₁₃)₄⁺CF₃SO₃⁻. This salt was tested in toluene, dichloromethane and chloroform with PP3. The DCM/PP3 system was the most successful system with >90% of the fluorous phosphonium salt remaining in the perfluorocarbon

phase. Both layers of the DCM/PP3 gave good accountability and were completely colourless; however the chloroform layer was extremely cloudy with the presence of the fine white salt giving indications that the salt was not likely to be soluble in this system. The toluene/PP3 system was colourless but a trace amount of the salt was present at the interface.

Solvent System	Partition % ^a Fluorous:Organic	Log P = C _{fluorous} /C _{organic}
PP3:DCM	90.2:9.8	0.96
PP3:Toluene	88.2:11.8	0.87
PP3:Chloroform	73.0:27.0	0.43

^a Average taken over three runs.

Table 13 Partition coefficients for $[\text{C}_6\text{F}_{13}\text{CH}_2\text{CH}_2\text{-P(4-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3]^+\text{CF}_3\text{SO}_3^-$

As expected, the tetraalkyl salt has a much higher partition coefficient than the perfluoroalkylated triarylphosphonium salt since it has already been established that $\text{P(CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3$ has a much higher partition coefficient, 99 %, than $\text{P(4-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3$, 81 %, in a PP3/toluene biphasic system. This triarylphosphonium salt was also tested in PFOB/toluene and PFOB/DCM (Table 14), taking into account the slight miscibility of organic solvents with PFOB, and the following results showed an increase in the solubility of the fluorinated phosphonium salt in the PFOB phase when toluene is used. This was to be expected because toluene is more soluble in PFOB than DCM (see Table 11).

Solvent System	Partition % ^a Fluorous:Organic	Log P = C _{fluorous} /C _{organic}
PFOB:Toluene	97.0:3.0	1.50
PFOB:DCM	89.1:10.9	0.91
PFOB:Chloroform	- ^b	- ^b

^a Average taken over three runs.

^b Salt was not soluble in either phase and sat at the bottom of the sample vial

Table 14 Partition coefficients for $[\text{C}_6\text{F}_{13}\text{CH}_2\text{CH}_2\text{-P(4-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3]^+\text{CF}_3\text{SO}_3^-$

The next salt to be tested was the benzyl triaryl phosphonium salt, $[\text{PhCH}_2\text{P(4-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3]^+\text{Br}^-$ (Table 15) which was tested in toluene and dichloromethane with PP3. The DCM/PP3 system gave >98 % of the fluoros salt residing in the perfluorocarbon phase whilst the toluene/PP3 showed slightly lower results, 88 %. The high partitioning of the benzyl triaryl salt in the DCM/PP3 system was expected, since the results for the benzyl alkyl salt, $\text{PhCH}_2\text{-P(CH}_2\text{CH}_2\text{C}_6\text{F}_{13})^+\text{Br}^-$ in DCM/PP3 also gave good partitioning into PP3 >90 % (Table 12). The benzyl triarylphosphonium was also tested in DCM/PFOB and toluene/PFOB and showed increased solubility when toluene/PFOB was used >93 % (Table 16). Both layers of the DCM and toluene with either PP3 or PFOB showed good accountability and were completely colourless.

Solvent System	Partition % ^a Fluorous:Organic	Log P = C _{fluorous} /C _{organic}
PP3:DCM	98.1:1.9	1.71
PP3:Toluene	88.0:12.0	0.87

^a Average taken over three runs.

Table 15 Partition coefficients for $[\text{PhCH}_2\text{-P(4-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3]^+\text{Br}^-]$

Solvent System	Partition % ^a Fluorous:Organic	Log P = C _{fluorous} /C _{organic}
PFOB:DCM	97.0:3.0	1.51
PFOB:Toluene	93.0:7.0	1.12

^a Average taken over three runs.

Table 16 Partition coefficients for $[\text{PhCH}_2\text{-P(4-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3]^+\text{Br}^-]$

The final fluorous salt to be tested was the butyl triarylphosphonium salt, *n*-Bu-P(4-C₆H₄C₆F₁₃)₃⁺CF₃SO₃⁻, which was tested with DCM and toluene with PP3. This salt proved to be insoluble in both systems with a white solid sitting at the interface and so PP3 was exchanged for PFOB and the systems were re-investigated. It can be seen from Table 17 that the PFOB/DCM system gave the best result with >80 % of the salt partitioned into the perfluorocarbon phase. All phases were colourless with no sign of a white solid at the interface resulting in better accountability and reproducibility with the PFOB systems.

Solvent System	Partition % ^a Fluorous:Organic	Log P = C _{fluorous} /C _{organic}
PFOB:DCM	81.5:18.5	0.64
PFOB:Toluene	66.9:33.1	0.31

^a Average taken over three runs.

Table 17 Partition coefficients for *n*-Bu-P(4-C₆H₄C₆F₁₃)₃⁺CF₃SO₃⁻

2.9 Retention and Recovery of Perfluorinated Phosphonium Salts on FRP Silica Gel.

Curran has elegantly shown that by attaching fluorous tags onto reagents, ligands or protecting groups, the straightforward separation of fluorous compounds from organic products by solid phase extraction over FRP silica gel can be carried out.²² The versatility of this method has been applied to parallel syntheses in which separation, purification and recovery are combined in one step. By incorporating the ability to recover and recycle these fluorous compounds, reduction in costs and work up procedures is accomplished.

The aim of this section was to carry out the separation and recovery of the fluorous-tagged phosphonium salts by solid phase extraction over FRP silica gel. This allows an alternative method to product/catalyst separation by liquid-liquid extraction in which several washes of the perfluorocarbon phase may be necessary. The important stage of the separation requires the retention of the fluorous-tagged phosphonium salt on the FRP column; this can be accomplished by eluting the column with a fluorophobic solvent (1) such as toluene, whilst recovery of the fluorous-tagged phosphonium salt is achieved by eluting the FRP silica gel column with a fluorophilic solvent (2) such as trifluoroethanol. TLC was used to monitor the movement of the salt on the FRP silica gel.

In order to carry out the separation and recovery of the fluorous phosphonium salt, dry loading of the fluorous salt onto the FRP silica gel was required. This was carried out by dissolving a known amount of the fluorous phosphonium salt (~100 mg) in reagent acetone, adding a known amount of FRP silica gel and removing the solvent by rotary evaporation.

This loaded FRP silica gel was then carefully added to a glass pipette containing fresh FRP silica gel (Figure 18).

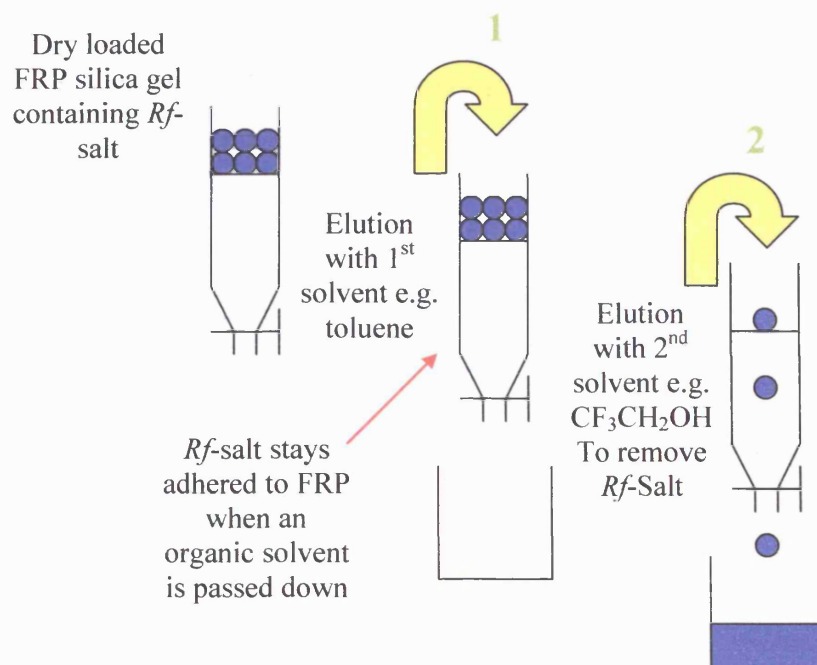


Figure 18 Retention and recovery from FRP silica gel

The first salt to be tested was the benzyl triaryl phosphonium salt, $\text{PhCH}_2\text{-P}(\text{C}_6\text{H}_4\text{C}_6\text{F}_{13})_3^+\text{Br}^-$ which was retained successfully on the short column of FRP silica gel with toluene. Both the butyl and the perfluoroalkylated triaryl phosphonium salts were tested with toluene and hexane and were retained on the FRP silica gel column. After assessing the retention of the fluorinated triarylphosphonium salts on the FRP silica gel, it was crucial that the perfluorinated salts could be removed and recovered from the FRP silica gel column. In the preliminary work, both acetone and methanol removed the fluorinated salts from the FRP silica gel column. Although the recovery was high, 70 – 80 %, it was not sufficient to be used on a large scale recovery process and an alternative solvent was required. It was thought that a hybrid solvent was required that contained a fluorine component, as well as organic components, within its structure. Benzotrifluoride (BTF) was an ideal solvent to try as it was known that the fluorinated phosphonium salts were soluble in it from the quaternisation processes and it seemed reasonable to assume that it would remove the fluorinated phosphonium salts from the column. However, only a moderate

recovery, <60 %, was obtained for all of the fluorous salts. Eventually, 2,2,2-trifluoroethanol, CF₃CH₂OH, gave good results that are shown in Table 18. The recovery of the fluorous phosphonium salts decreased with increasing fluorine content; PhCH₂-P(C₆H₄C₆F₁₃)₃⁺Br⁻ (91 %) compared to the butyl triarylphosphonium salt, *n*-C₄H₉-P(C₆H₄C₆F₁₃)₃⁺CF₃SO₃⁻ (86 %). The perfluoroalkylated phosphonium salt, C₆F₁₃C₂H₄-P(C₆H₄C₆F₁₃)₃⁺CF₃SO₃⁻, shows the lowest recovery of all the fluorous phosphonium salts (83 %) which could be accounted for by the large fluorine content.

<i>Rf</i> -Salt ^a	1 st Solvent	2 nd Solvent	Recovered Salt (%)
[PhCH ₂ -P(C ₆ H ₄ C ₆ F ₁₃) ₃ ⁺ Br ⁻]	Toluene	CF ₃ CH ₂ OH	91.3
[C ₆ F ₁₃ C ₂ H ₄ -P(C ₆ H ₄ C ₆ F ₁₃) ₃ ⁺ CF ₃ SO ₃ ⁻]	Hexane	CF ₃ CH ₂ OH	83.7
[<i>n</i> -C ₄ H ₉ -P(C ₆ H ₄ C ₆ F ₁₃) ₃ ⁺ CF ₃ SO ₃ ⁻]	Hexane or Toluene	CF ₃ CH ₂ OH	86.0

^a These runs were carried out three times with good reproducibility and accountability.

Table 18 Retention and recovery from FRP silica gel

2.10 Conclusions.

A small series of heavy fluororous trialkyl and triaryl phosphonium salts were synthesised in good yields by the quaternisation of the trialkyl phosphine, $\text{P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3$, and the triaryl phosphine, $\text{P}(4\text{-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3$, respectively. It was demonstrated that the long reaction times required for the quaternisation could be reduced dramatically by using microwave conditions and $\text{PhCH}_2\text{-P}(4\text{-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3^+\text{Br}^-$ was prepared in 15 minutes under microwave conditions compared to 30 hours under conventional heating. Liquid-liquid extractions of the tetraalkyl phosphonium salt, $\text{P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_4^+\text{CF}_3\text{SO}_3^-$ and the $\text{PhCH}_2\text{-P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3^+\text{Br}^-$ were carried out with excellent separation obtained, 94-97 %. The triaryl phosphonium salts were also tested under liquid-liquid extractions with satisfactory results obtained. The perfluoroalkylated triaryl phosphonium salt, $[\text{C}_6\text{F}_{13}\text{CH}_2\text{CH}_2\text{-P}(4\text{-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3]^+\text{CF}_3\text{SO}_3^-$, gave good results when toluene was used with PFOB (97 %). Whilst surprisingly good results for the benzyl triaryl phosphonium salt, $[\text{PhCH}_2\text{-P}(4\text{-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3]^+\text{Br}^-$, was obtained in a DCM/PP3 system (98 %). The butyl triaryl phosphonium salt, $[\text{n-C}_4\text{H}_9\text{-P}(4\text{-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3]^+\text{CF}_3\text{SO}_3^-$, was insoluble in PP3 solvent systems whilst reasonable results were obtained in the DCM and PFOB system (81 %). Solid phase extractions were carried out over FRP silica gel. All of the fluororous triarylphosphonium salts could be retained successfully on the FRP silica gel column by using either toluene or hexane and no leaching was observed. Recovery of the fluororous triarylphosphonium salts from the FRP column was achieved by using 2,2,2-trifluoroethanol with good yields obtained. It appears that separation and recovery of the benzyl triaryl phosphonium salt is best achieved by liquid-liquid extraction using DCM/PP3, 98 %, compared to solid phase extraction over FRP silica gel (86 %). Although high partition coefficients are obtained for the perfluoroalkylated and butyl triaryl phosphonium salts, the use of PFOB makes recovery difficult given that PFOB with either DCM or toluene are considerably miscible. Continuous washing of the PFOB phase would be essential for removing any excess reagent(s) or product(s) subsequently leaving the fluororous phosphonium salt as pure as possible for recycling.

2.11 References.

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Chapter 3

3.0 Synthesis and Applications of Fluorous-Tagged Phase Transfer Catalysts.

3.1 Picrate Extractions.

Before examining the applications of the novel perfluorinated phosphonium salts in a phase transfer catalysed reaction, it was decided to first test all of the fluorous-tagged phosphonium salts in picrate extractions. The information obtained will show the different extraction capabilities of each phosphonium salt.

It is well known that picrate anions are amongst one of the easiest anions to transfer to the organic phase under phase transfer conditions. The complexation ability and selectivity of some crown ethers can be obtained by extraction experiments using potassium picrate (Figure 19).¹ Crown ethers are insoluble in water whilst the corresponding metal salts are insoluble in the organic solvent. The crown ether can complex the metal cation and the host-guest molecule is then accompanied into the organic phase by the picrate counter anion. The efficiency of this extraction process can be measured by determining the amount of picrate extracted into the organic phase using UV-Visible spectroscopy.

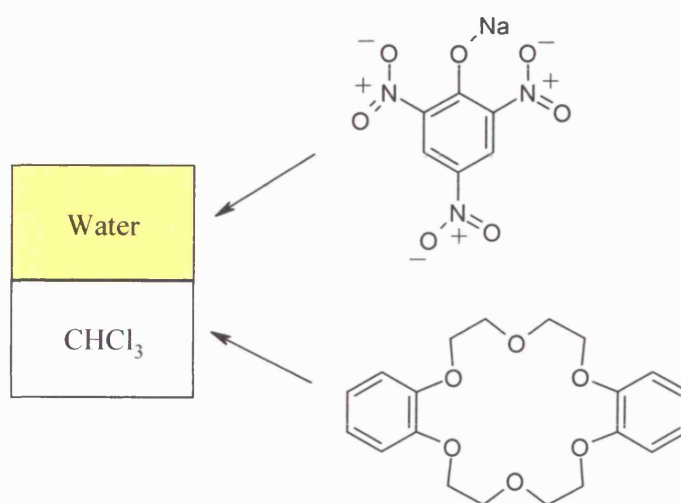


Figure 19 Picrate extractions

The first task for assessing the fluorine-tagged phosphonium salts extraction capabilities was to calibrate the UV-Visible spectrometer. This involved measuring the absorbance of several aqueous solutions of potassium picrate of known concentrations which were recorded and a graph of absorbance versus concentration (Figure 20) was plotted.

In order to carry out the reactions, a known amount of a fluorine tagged phosphonium salt in BTF was added to a known amount of potassium picrate in water. The reactions were carried out using a 1:1 ratio of perfluorinated phosphonium salt to potassium picrate. The two phases were stirred for 30 minutes before allowing to settle for 30 minutes. Samples from the aqueous phase were removed and UV-Visible spectroscopy carried out. Since the potassium picrate has an intense yellow colour, the picrate concentration in the aqueous phase before and after the reaction can be determined by UV-Visible spectroscopy (wavelength 356 nm). The extraction ability was calculated according to the following equations:

$$\text{Percentage picrate extracted} = (\text{Abs}_{(\text{before})} - \text{Abs}_{(\text{after})}) / \text{Abs}_{(\text{before})} \times 100$$

$$\text{Abs}_{(\text{before})} = \text{Absorbance of picrate solution before extraction}$$

$$\text{Abs}_{(\text{after})} = \text{Absorbance of picrate solution after extraction}$$

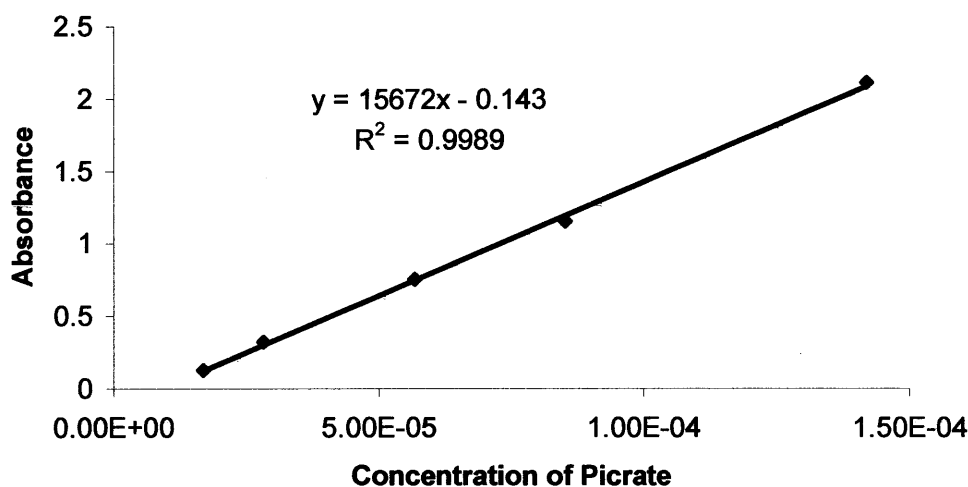


Figure 20 Calibration of UV/Visible spectrometer

Reactions containing no fluorous phosphonium salt were carried out with BTF and aqueous potassium picrate which resulted in the BTF layer remaining colourless at the end of the reaction. The extraction of the picrate anion into the organic phase was examined for each of the fluorous-tagged trialkyl and triaryl phosphonium salts and the results were compared directly with the standard phase transfer catalysts, tetrabutyl-*n*-ammonium bromide (TBAB) and benzyl triphenylphosphonium bromide. All the reactions were carried out three times with good accountability and reproducibility obtained in all cases.

All of the triaryl phosphonium salts extracted high percentages of the picrate anion from the aqueous phase into the organic phase (Table 19). Overall, the following series for the perfluorinated aryl phosphonium salts can be assembled: $\text{PhCH}_2\text{-P(4-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3^+\text{Br}^- > \text{C}_6\text{F}_{13}\text{CH}_2\text{CH}_2\text{-P(4-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3^+\text{CF}_3\text{SO}_3^- > \text{n-C}_4\text{H}_9\text{-P(4-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3^+\text{CF}_3\text{SO}_3^-$. It is not known whether the use of the bromide ion in $\text{PhCH}_2\text{-P(4-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3^+\text{Br}^-$, is acting as a better leaving group compared to the triflate anion, CF_3SO_3^- . A surprisingly low result was obtained for TBAB and could be accounted for by the lack of solubility in BTF.

The same picrate extractions were carried out for the trialkyl phosphonium salts (Table 20). Only moderate success for the extraction of the picrate anion to the organic phase was obtained, compared to the high success seen with the triaryl phosphonium salts. It

can be seen that the benzyl trialkyl phosphonium salt, gave poor extractions, 68 % whilst surprisingly, the butyl salt gave the best results, 86 %. Unfortunately, the differences in extraction capability of the fluorous phosphonium salts could not be determined by the nature of the anion of the phosphonium salts. Overall, it has become apparent that the aromatic nature of the solvent, benzotrifluoride, may facilitate the high picrate transfer of the triaryl phosphonium salts compared to the trialkyl phosphonium salts.

<i>F-Salt</i>	Abs. of Aq Phase	% Ext to Org Phase	Average
PhCH ₂ P(ArRf) ⁺ Br ⁻	a) 0.00	100	100 %
PhCH ₂ P(ArRf) ⁺ Br ⁻	b) 0.00	100	
PhCH ₂ P(ArRf) ⁺ Br ⁻	c) 0.00	100	
Blank	d) 1.276	0.0	
C ₆ F ₁₃ C ₂ H ₄ -P(ArRf) ⁺ CF ₃ SO ₃ ⁻	a) 0.034	97.2	95.9 % ± 1.2
C ₆ F ₁₃ C ₂ H ₄ -P(ArRf) ⁺ CF ₃ SO ₃ ⁻	b) 0.053	95.6	
C ₆ F ₁₃ C ₂ H ₄ -P(ArRf) ⁺ CF ₃ SO ₃ ⁻	c) 0.062	94.8	
Blank	d) 1.214	0.0	
C ₄ H ₉ -P(ArRf) ⁺ CF ₃ SO ₃ ⁻	a) 0.223	85.6	84.6 % ± 1.8
C ₄ H ₉ -P(ArRf) ⁺ CF ₃ SO ₃ ⁻	b) 0.223	85.6	
C ₄ H ₉ -P(ArRf) ⁺ CF ₃ SO ₃ ⁻	c) 0.271	82.5	
Blank	d) 1.551	0.0	
PhCH ₂ -PPh ₃ ⁺ Br ⁻	0.099	93.7	94.4 % ± 0.6
PhCH ₂ -PPh ₃ ⁺ Br ⁻	0.079	95.0	
PhCH ₂ -PPh ₃ ⁺ Br ⁻	0.087	94.5	
Blank	1.573	0.0	
N(C ₄ H ₉) ₄ ⁺ Br ⁻	0.412	72.0	71.6 % ± 0.7
N(C ₄ H ₉) ₄ ⁺ Br ⁻	0.422	71.3	
N(C ₄ H ₉) ₄ ⁺ Br ⁻	0.419	71.5	
Blank	1.470	0.0	

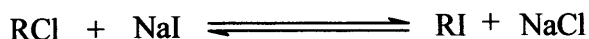
Table 19 Picrate extractions of the perfluorinated triaryl phosphonium salts

<i>F-Salt</i>	Abs. of Aq Phase	% Ext to Org Phase	Average
$\text{P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_4^+\text{CF}_3\text{SO}_3^-$	0.410	73.5	73.8 % \pm 0.4
$\text{P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_4^+\text{CF}_3\text{SO}_3^-$	0.407	73.7	
$\text{P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_4^+\text{CF}_3\text{SO}_3^-$	0.399	74.2	
Blank	1.547	0.0	
$\text{PhCH}_2\text{-P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3^+\text{Br}^-$	0.526	65.2	67.7 % \pm 1.6
$\text{PhCH}_2\text{-P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3^+\text{Br}^-$	0.479	67.4	
$\text{PhCH}_2\text{-P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3^+\text{Br}^-$	0.433	70.5	
Blank	1.471	0.0	
$\text{C}_4\text{H}_9\text{-P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3^+\text{CF}_3\text{SO}_3^-$	0.299	84.0	85.8 % \pm 1.5
$\text{C}_4\text{H}_9\text{-P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3^+\text{CF}_3\text{SO}_3^-$	0.198	86.2	
$\text{C}_4\text{H}_9\text{-P}(\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13})_3^+\text{CF}_3\text{SO}_3^-$	0.184	87.2	
Blank	1.432	0.0	
$\text{PhCH}_2\text{-PPh}_3^+\text{Br}^-$	0.099	93.7	94.4 % \pm 0.6
$\text{PhCH}_2\text{-PPh}_3^+\text{Br}^-$	0.079	95.0	
$\text{PhCH}_2\text{-PPh}_3^+\text{Br}^-$	0.087	94.5	
Blank	1.573	0.0	
$\text{N}(\text{C}_4\text{H}_9)_4^+\text{Br}^-$	0.412	72.0	71.6 % \pm 0.7
$\text{N}(\text{C}_4\text{H}_9)_4^+\text{Br}^-$	0.422	71.3	
$\text{N}(\text{C}_4\text{H}_9)_4^+\text{Br}^-$	0.419	71.5	
Blank	1.470	0.0	

Table 20 Picrate extractions of the perfluorinated trialkyl phosphonium salts

3.2 Introduction to Halide Exchange.

The Finkelstein reaction shown in Scheme 48 represents a halide reaction which is an equilibrium process. The reaction involves the formation of iodides from chlorides using a polar solvent such as acetone.² NaI is soluble in acetone which causes the equilibrium to be forced to the right by the precipitation of NaCl. This method can also be applied to a two phase system in the presence of a phase transfer catalyst.



Scheme 48 Finkelstein reaction

The reaction can be applied to the formation of bromides under bromide-chloride exchange which usually occurs under solid-liquid phase transfer conditions, though there are few reports investigating the liquid-liquid systems. A number of factors can affect these solid-liquid systems such as the degree of hydration within the system which can greatly affect the transfer of the anion and its reactivity. Excess water within a system can be detrimental to the reaction, causing rates to fall and thereby reducing displacement yields. Loupy *et al.* reported the conversion of alkyl chlorides to their corresponding bromides using tetra-*n*-hexylammonium bromide (THAB) and stiochiometric amounts of metal bromides under solid-liquid phase transfer conditions.³ The reactions were carried out without any solvents and the amount of water was limited to 5 % w/w of the calcium bromide to give 90 - 95 % conversion. With larger amounts of water in the system, conversions were reduced.

Sasson and Loupy investigated the equilibrium processes in halide exchange reactions and the effect of water on the system.⁴ The reactions were carried out in sealed tubes and the final equilibrium composition was determined by gc analysis of the organic phase. It was observed that with a sufficient amount of water, the reaction mixture consisted of two non-miscible phases and upon decreasing the amount of water within the system, a critical concentration was achieved in which a precipitate was formed during the course of the reaction. They proposed that the reaction was dependent on the composition of the

aqueous phase and the salts involved. Water was required for hydration of the metal cations and was essential for the extraction process in phase transfer catalysis i.e. ions which are not hydrated or not in solution can not be extracted. Lithium and calcium bromides are not only more soluble but their corresponding chloride salts precipitate out of solution more readily. When only a small amount of water is present in the system, calcium and lithium bromide will hydrate owing to a high affinity to water while the corresponding chlorides will remain dry and thus inert to phase transfer exchange processes.

3.3 Halide Exchange under Solid-Liquid Phase Transfer Conditions.

The catalytic applications of the perfluorinated triaryl phosphonium salts were investigated under solid-liquid conditions in a simple model halide exchange reaction of benzyl chloride to benzyl bromide. The reactions were carried out in BTF using lithium bromide with 5 mol % of phase transfer catalyst at 110 °C for 6 hours and the reactions were monitored by gc using biphenyl as the internal standard. The first task was to calibrate the GC for benzylbromide with a fixed amount of an internal standard, biphenyl. Biphenyl was used in the reaction mixture since it was inert to the reaction conditions. Nine different concentrations of benzyl bromide in BTF with biphenyl were prepared and the samples run on the GC. The reactions were carried out twice and the averages are presented in Figure 21. Both the butyl and perfluoroalkylated phosphonium salts gave good conversions to benzyl bromide after 6 hours and seemed to be slightly more reactive than the standard phase transfer catalyst, THAB. However, the benzyl phosphonium bromide was much less active and it is difficult to determine whether this is because of the structure of the cation or whether the bromide anion is less efficient at undergoing anion exchange under these conditions. It was also important to determine that there was only 13 % conversion to benzyl bromide after 6 hours when there is no phase transfer catalyst present.

Figure 22 compares the reactivity of each of the phase transfer catalysts under solid-liquid conditions after 1 hour using different volumes of benzotrifluoride (2 cm³ and 10

cm³). As expected, the rate of the reactions was higher in the smaller volume of solvent due to the increase in the concentration of the reactants. This time, however, the standard phase transfer catalyst, THAB, was more reactive than the butyl phosphonium salt and the benzyl phosphonium salt still proved to be fairly unreactive.

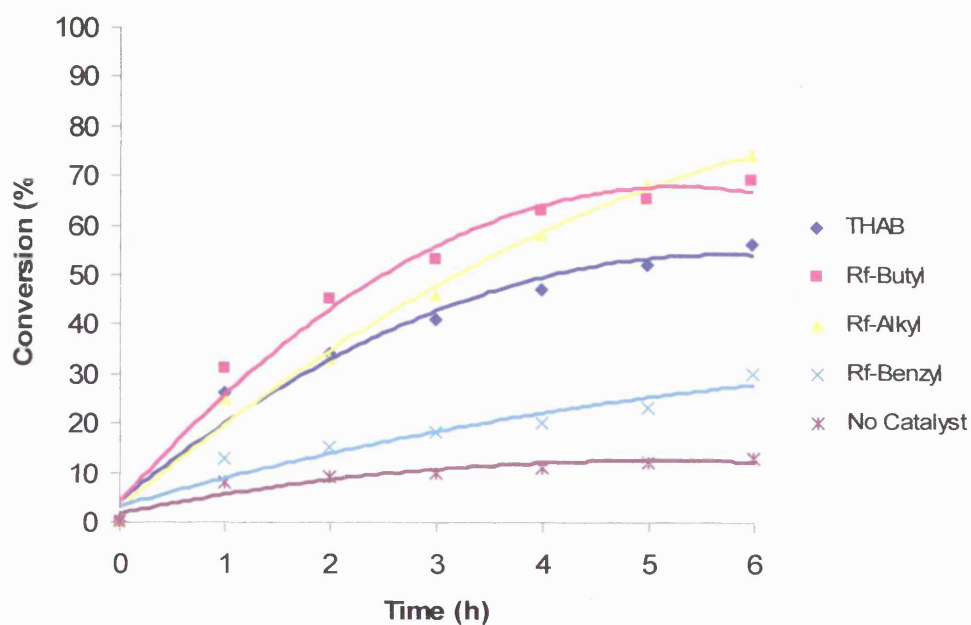


Figure 21 Conversion of BnCl to BnBr under solid-liquid conditions using BTf (10 cm³)

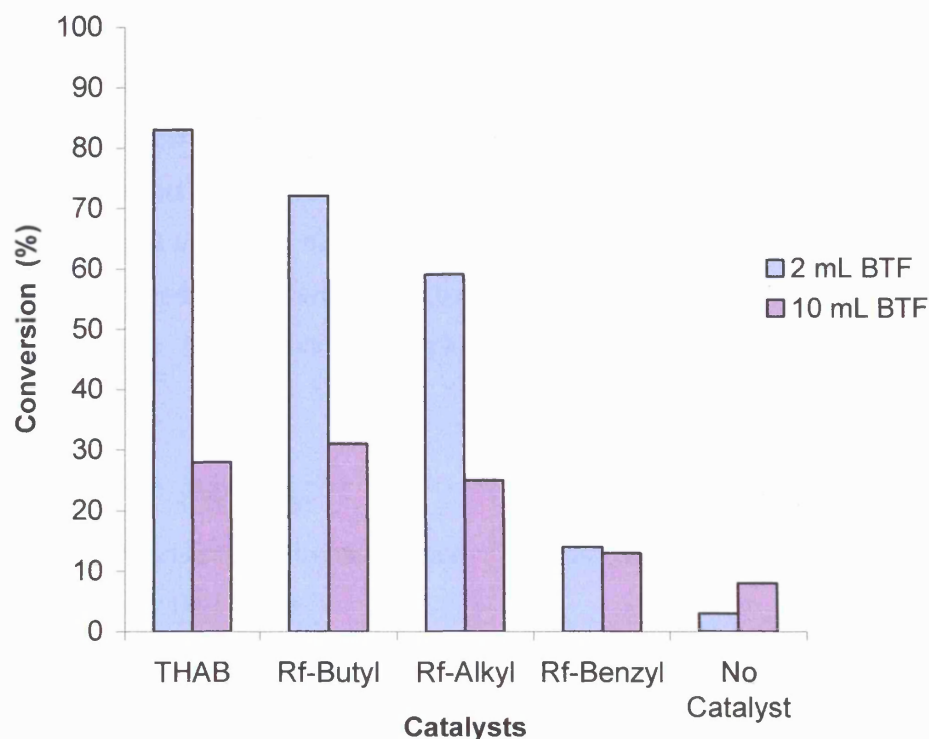


Figure 22 Conversion of BnCl to BnBr after 1 hour under solid-liquid conditions using different volumes of BTF

All of the perfluorinated triaryl phosphonium salts were investigated in the halide exchange of 1-chlorooctane to 1-bromooctane using lithium bromide under the same reaction conditions established previously. It has been shown that this reaction using THAB takes 18 hours using neat reactants without the presence of solvent.³ Initially, studies were carried out using 10 mL of BTF, but conversions to octyl bromide were extremely slow for all of the perfluorinated triaryl phosphonium salts. Since reducing the solvent increases the rate of reaction, the volume of BTF was reduced to 2 mL and Table 21 compares the reactivity of each phase transfer catalyst under solid/liquid conditions. It is clear that the standard phase transfer catalysts, THAB and TBAB, are the most reactive catalysts, and the

reactions were almost complete in 2 hours (93 % and 90 % respectively). However, it is surprising that the reverse order of reactivity of the perfluorinated catalysts was observed compared to the halide exchange of benzyl chloride. The benzyl phosphonium salt now shows the highest reactivity and gives the greatest conversion (91 %) after 22 hours. Both the butyl and the perfluoroalkylated triaryl phosphonium salts have lower reactivity with the perfluoroalkylated triaryl phosphonium salt giving the lowest conversion, 43 %. It was also established that there was no conversion to 1-bromooctane when there was no phase transfer catalyst present. In conclusion, both THAB and TBAB performed much more efficiently than the perfluorinated phosphonium salts under concentrated solid-liquid conditions.

PTC, LiBr 1-chlorooctane → 1-bromooctane BTF (2 cm³)	Time (h)	Conversion (%)
THAB	2	93
TBAB	2	90
$[\text{PhCH}_2\text{-P}(\text{C}_6\text{H}_4\text{C}_6\text{F}_{13})_3]^+\text{Br}^-$	22	91
$[\text{n-C}_4\text{H}_9\text{-P}(\text{C}_6\text{H}_4\text{C}_6\text{F}_{13})_3]^+\text{CF}_3\text{SO}_3^-$	22	68
$[\text{C}_6\text{F}_{13}\text{C}_2\text{H}_4\text{-P}(\text{C}_6\text{H}_4\text{C}_6\text{F}_{13})_3]^+\text{CF}_3\text{SO}_3^-$	22	43
No Phase Transfer Catalyst	22	0

Table 21 Percentage conversion to octylbromide

3.4 Halide Exchange under Liquid-Liquid Phase Transfer Conditions.

An investigation into the halide exchange of 1-bromooctane to 1-iodooctane under solid-liquid conditions was carried out. The first task for analysis was to calibrate the gc machine by including a fixed amount of the internal standard, biphenyl. The area of several

solutions of known concentration of 1-iodooctane and biphenyl was recorded and a graph of ratio against concentration was plotted.

The catalytic applications of each of the fluorous phosphonium salts were examined in the halide exchange of 1-bromooctane to 1-iodooctane under solid-liquid conditions. The reactions were carried out in refluxing BTF using a 5 mole excess of KI with 1-bromooctane in the presence of 2 mol % of catalyst. The percentage conversion was calculated by gc using biphenyl as the internal standard. Each reaction was carried out twice and the averages are presented in Table 22. The reactions with perfluorinated and non-fluorinated phosphonium salts under solid-liquid conditions were not complete within 24 hours. As expected, TBAB gave the highest conversion to octyl iodide (79 %) compared to the perfluorinated phosphonium salts. The standard phase transfer catalyst, benzyltriphenylphosphonium bromide, was much less reactive than TBAB, giving only 47 % conversion but this could be accounted for by the lack of solubility of benzyltriphenylphosphonium bromide in BTF. The highest conversion obtained by a perfluorinated phosphonium salt was for the butyl phosphonium salt, which gave 56 % conversion to the octyl iodide, whilst the perfluoroalkyl and benzyl phosphonium salts proved to be rather unreactive (25 % and 18 % respectively).

PTC, KI 1-bromooctane → 1-iodooctane BTf (4 cm ³)	% Conversion after 24 h
TBAB	79
[n-C ₄ H ₉ -P(C ₆ H ₄ C ₆ F ₁₃) ₃] ⁺ CF ₃ SO ₃ ⁻	56
(PhCH ₂ -PPh ₃) ⁺ Br ⁻	47
[C ₆ F ₁₃ C ₂ H ₄ -P(C ₆ H ₄ C ₆ F ₁₃) ₃] ⁺ CF ₃ SO ₃ ⁻	25
[PhCH ₂ -P(C ₆ H ₄ C ₆ F ₁₃) ₃] ⁺ Br ⁻	18
No Phase Transfer Catalyst	0

Table 22 Solid-liquid reactions monitored after 24 hours

In the presence of an aqueous solution of KI, all of the fluorous-tagged phosphonium salts undergo anion exchange to the iodide ion. This can be seen by the change in chemical shifts in the ³¹P NMR spectra (Table 23) and by mass spectroscopy. As expected, the benzyl salt shows complete anion exchange since the bromide anion is the easiest anion to transfer and exchange compared to the triflate group.

F-Salt	³¹ P NMR (ppm)	³¹ P NMR after iodination PTC with KI (ppm)
PhCH ₂ -P(4-C ₆ H ₄ Rf) ₃ ⁺ Br ⁻	25.34	25.64
n-C ₄ H ₉ -P(4-C ₆ H ₄ Rf) ₃ ⁺ CF ₃ SO ₃ ⁻	25.99	26.33
RfCH ₂ CH ₂ -P(4-C ₆ H ₄ Rf) ₃ ⁺ CF ₃ SO ₃ ⁻	27.01	27.10

Table 23 ³¹P NMR data before and after iodination

Exactly the same reactions were carried out under liquid-liquid conditions using a water (2 mL) and benzotrifluoride (4 mL) biphasic system containing 2 mol % of the phase transfer catalyst and heating at 110 °C for 16 hours. The reactivity of each of the catalysts was monitored by gc every two hours and the results are presented in Figure 23. The rate of the reaction carried out under liquid-liquid conditions was much quicker than the previous reactions under solid-liquid conditions. Although TBAB was the most efficient phase transfer catalyst, 97 % conversion in 6 h, both the butyl and benzyl perfluorinated phosphonium salts gave high conversions to the product after 16 hours (97 % and 80 % conversion respectively). Interestingly, the standard phase transfer catalyst, benzyltriphenylphosphonium bromide, gave a slightly lower conversion, (68 %) than the fluorinated analogue. Once again, the catalytic activity of the phosphonium salt containing four fluorinated ponytails was much lower (49 % conversion in 12 hours). Since all of the reactions proceeded at a much faster rate than the reaction under solid-liquid conditions, the presence of water seems to be crucial for the efficient transfer of the iodide anion into the organic phase.

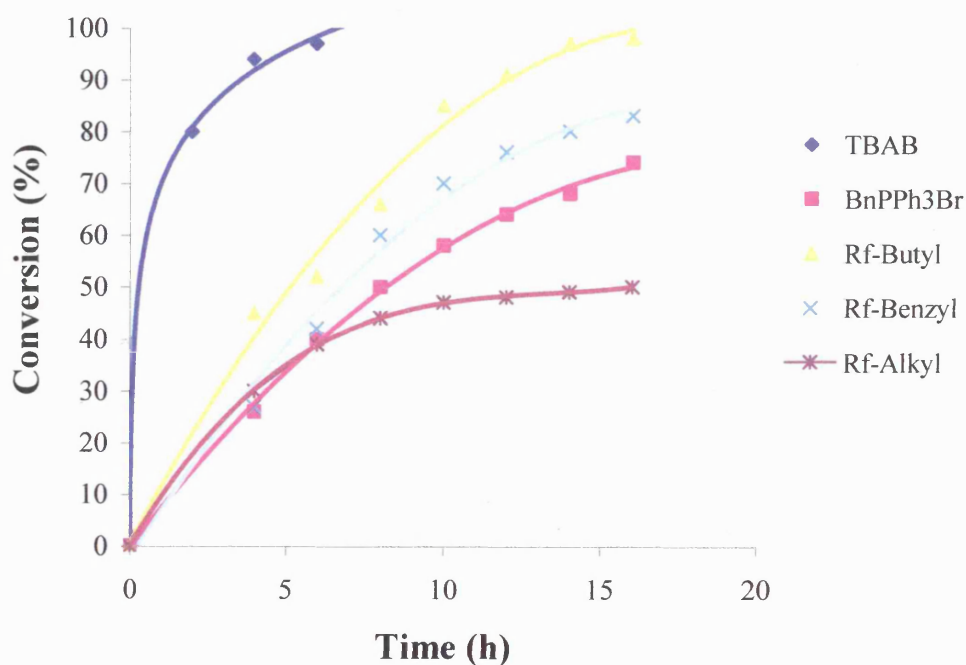


Figure 23 Reactions under liquid-liquid conditions

3.5 Separation and Recovery Studies.

The separation and recovery of the fluorous-tagged phosphonium salts from the organic products was investigated, so that the recovered phase transfer catalyst could be reused in a sequential reaction. Preliminary studies into the separation and recovery of the fluorous-tagged phosphonium salts from organic products was carried out on halide exchange reactions using two methods: 1) washing with hexane to remove all organic products and leave the fluorous salt, which is insoluble in hexane (Table 24); 2) recovery by FRP silica gel using the appropriate solvents already established in Chapter 2 (Table 18).

The halide exchange of benzyl chloride to benzyl bromide was carried out using the butyl triaryl phosphonium salt. After the reaction the BTF was removed by rotary evaporation to leave a viscous oily mixture which consisted of the butyl triaryl phosphonium salt, benzyl bromide and biphenyl. The mixture was washed with hexane and placed in dry ice to precipitate out the fluorous phosphonium salt (Table 24). This was carried out several times and the hexane washes combined and solvent removed. ^1H , ^{19}F and ^{31}P NMR spectroscopy of the butyl triaryl phosphonium salt showed small amounts of biphenyl and the fluorous triaryl phosphine oxide. Whilst the combined hexane washes contained benzyl bromide and biphenyl with no sign of the butyl triaryl phosphonium salt.

The separation and recovery of the benzyl triaryl phosphonium salt used in the halide exchange of 1-chlorooctane to 1-bromooctane over fluorous silica gel was carried out. To begin the separation and recovery process, the mixture of fluorous and organic products were dry loaded onto FRP silica gel (Table 25). This was accomplished by dissolving the mixture in a small amount of reagent acetone, adding the FRP silica gel (~ 100 mg) and removing the acetone by rotary evaporation. The loaded FRP silica gel was then loaded onto fresh FRP silica gel in a small column. Eluting with toluene removed the organic products, whilst elution with trifluoroethanol recovered the benzyl triaryl phosphonium salt in low yields (47-67 %) as well as the fluorous triaryl phosphine oxide. The organic fraction recovered contained 1-bromooctane and the biphenyl; however, the ^1H , ^{31}P , and ^{19}F NMR spectra showed the presence of the fluorous triaryl phosphine as

well. The fact that both the fluorous triaryl phosphine oxide and triaryl phosphine were present in the separation and recovery methods indicates some kind of decomposition was occurring during the PTC reactions.

<i>Rf</i> -Catalyst	Wt of Catalyst used in Reaction	Wt of Catalyst Recovered	% Recovered ^a
$[\text{C}_4\text{H}_9\text{-P}(\text{C}_6\text{H}_4\text{C}_6\text{F}_{13})_3]^+\text{CF}_3\text{SO}_3^-$	0.355 g	0.292 g	82 %
$[\text{C}_4\text{H}_9\text{-P}(\text{C}_6\text{H}_4\text{C}_6\text{F}_{13})_3]^+\text{CF}_3\text{SO}_3^-$	0.355 g	0.301 g	85 %
$[\text{C}_4\text{H}_9\text{-P}(\text{C}_6\text{H}_4\text{C}_6\text{F}_{13})_3]^+\text{CF}_3\text{SO}_3^-$	0.355 g	0.289 g	81 %

^a Contained the internal standard biphenyl (¹H NMR), as well as phosphine oxide by ³¹P NMR spectroscopy.

Table 24 Separation by hexane washes

<i>Rf</i> -Catalyst	Wt of Catalyst used in Reaction	Wt of Catalyst Recovered ^a	% Recovered ^b
$[\text{PhCH}_2\text{-P}(\text{C}_6\text{H}_4\text{C}_6\text{F}_{13})_3]^+\text{Br}^-$	0.347 g	0.193 g	56 %
$[\text{PhCH}_2\text{-P}(\text{C}_6\text{H}_4\text{C}_6\text{F}_{13})_3]^+\text{Br}^-$	0.347 g	0.162 g	47 %
$[\text{PhCH}_2\text{-P}(\text{C}_6\text{H}_4\text{C}_6\text{F}_{13})_3]^+\text{Br}^-$	0.347 g	0.233 g	67 %
$[\text{PhCH}_2\text{-P}(\text{C}_6\text{H}_4\text{C}_6\text{F}_{13})_3]^+\text{Br}^-$	0.347 g	0.239 g	67 %

^a Solvent used:- trifluorotoluene

^b Contained the phosphine and phosphine oxide by ³¹P NMR spectroscopy.

Table 25 Separation by FRP silica gel

3.6 Decomposition of Phosphonium Salts.

Phosphonium salts have a wide range of decomposition routes compared to the ammonium salts and the thermally stable crown ethers and cryptands. Attack at the α -carbon atom in phosphonium salts can occur from excessive heating to give the tertiary phosphine and the organic halide byproducts; it is sometimes referred to as the *reverse of quaternisation* (Scheme 49).⁵ The decomposition of long chain phosphonium salts can lead to the

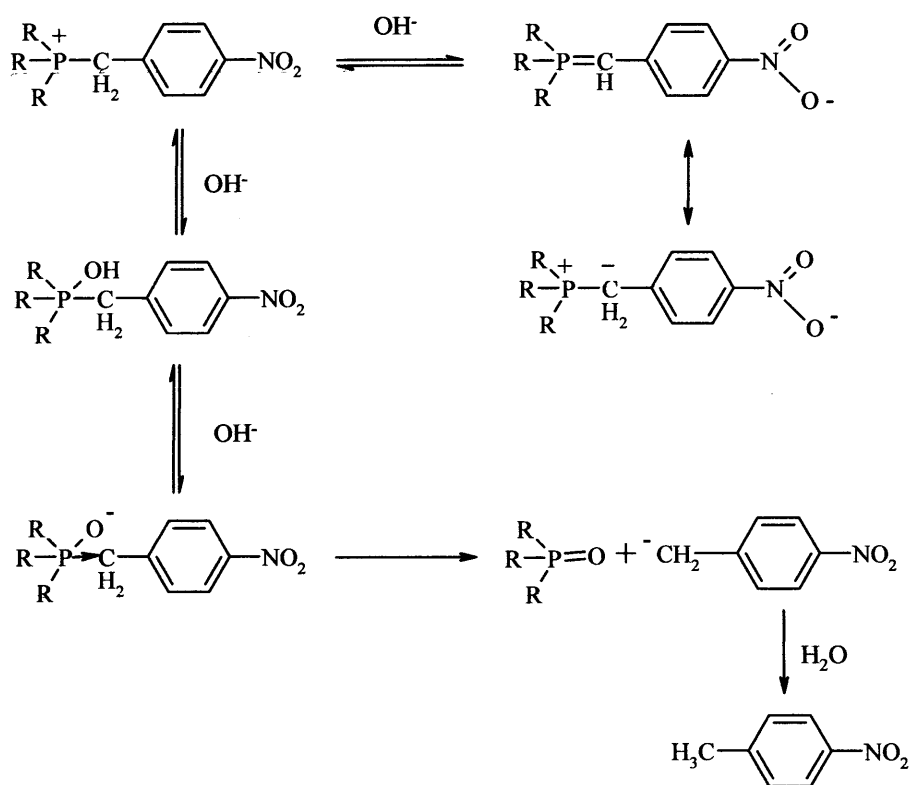
formation of varying amounts of hydrocarbons because those salts which contain several different substituents on the phosphorus can cleave in several alternate ways.



Scheme 49 Reverse of quaternisation

The positively charged phosphorus atom in quaternary phosphonium salts is prone to nucleophilic attack. For example, aqueous alkali solutions can be a source of OH^- ions and the hydroxide ion (OH^-) can carry out a nucleophilic displacement to give the phosphine oxide and a hydrocarbon.

The decomposition of phosphonium compounds passes through a pentacovalent state because the ionized phosphorane is believed to be sufficiently energetic to expel the carbanion and one example of this mechanism is the alkaline decomposition of *p*-nitrobenzyl substituted phosphonium bromide as shown in Scheme 50.⁶ Khalil and Aksnes also carried out decomposition studies of tetraphenylphosphonium chloride in a dioxane – D_2O liquid-liquid biphasic system and confirmed the decomposition mechanism as outlined in Scheme 50.^{7,8}

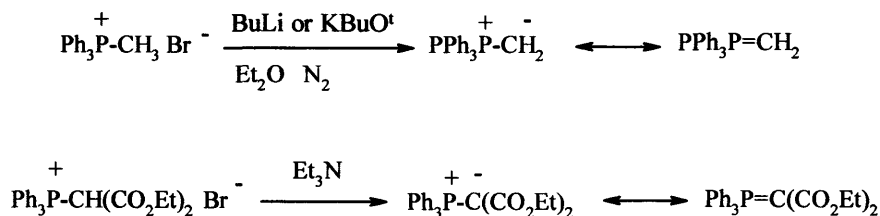


Scheme 50 Decomposition of *p*-nitrobenzyl substituted phosphonium bromide.

A number of factors affect the stability of quaternary phosphonium salts in aqueous-organic biphasic systems; these include the nature of the R group attached to the phosphorus atom and its effectiveness as a leaving anion, the solvent which is used, the concentration of base in the aqueous phase and the temperature of the reaction.⁹ The benzyl group has a weaker inductive effect compared to, for example an ethyl group, and therefore, it does not delocalize the positive charge on the phosphorus as effectively as an ethyl group. It was found that the rate of hydrolysis increases strongly when alkyl groups are substituted by phenyl groups in hydroxide and alkoxide promoted decomposition studies. The benzyl group is ejected in favor of the alkyl group due to the stabilization of the carbanion formed during the third step of the mechanism (Scheme 50). In these cases, the benzyl leaving group is sufficiently activated to be directly displaced by a hydroxide or alkoxide ion.

The decomposition can also be affected by the use of polar solvents. For example, the decomposition of tetraphenylphosphonium bromide in acetone shows a higher rate of decomposition compared to other less polar solvents. Temperature can also play a crucial role in the decomposition of phosphonium salts. Landini *et al.* tested several phosphonium salts, Bu-PPh₃⁺X⁻ and (hexadecyl)P(butyl)₃⁺X⁻ under increasing temperature conditions and alkaline concentrations.¹⁰ They found that by increasing the temperature and alkaline concentration in the system, decomposition of the phosphonium salt increased compared to analogous ammonium salts.

Finally, bases may attack the α -hydrogen of a phosphonium salt in a number of ways depending on the salt, its substituents, the base and the conditions used. The strength of the base required to form the ylide depends on the acidity of the α -hydrogen atom and is influenced by neighboring substituents of the α -carbon atom. If the substituents in the salt are able to stabilize the negative charge, then the protons of the α -carbon will be removed more easily and a stable phosphonium ylide will be formed. Several examples include the treatment of methyltriphenyl phosphonium bromide with BuLi or BuO^tK and diethyl malonate triphenyl phosphonium bromide with triethylamine to give the corresponding ylides (Scheme 51).¹¹



Scheme 51 Examples of ylide formation

3.7 Decomposition Studies.

The decomposition of the perfluorinated phosphonium salts were studied at room temperature (22 – 26 °C) and under refluxing conditions (110 °C) as detailed in Tables 26 and 27. The reactions were carried out using the multireactor with 50 – 60 mg of fluorosalt in BTF (4 cm³) and, if required, water (2 cm³).

The overall decomposition was more pronounced under refluxing conditions than at room temperature. At room temperature the butyl and perfluoroalkylated triaryl phosphonium salts were more sensitive to decomposition to the triaryl phosphine oxide than the benzyl salt. The presence or absence of KI did not affect the decomposition at room temperature; however, differences are more distinct at high temperatures, indicating a thermal stability problem. When the benzyl salt was refluxed in BTF the phosphine was produced along with the phosphine oxide, 5 % and 3 % respectively. This suggests that the decomposition occurs from the reverse of quaternisation with the phosphine being oxidized by the surrounding air to phosphine oxide. Neither the butyl nor the perfluoroalkylated triaryl phosphonium salts show any decomposition to the phosphine or the phosphine oxide under refluxing BTF. The presence of large amounts of phosphine was also observed when the benzyl salt was refluxed under solid-liquid conditions (KI/BTF) (17 %). However, no phosphine was obtained when the butyl or the perfluoroalkylated salts were refluxed under the same conditions and only the presence of the phosphine oxide, 6-7 %, was observed in each case. When the benzyl and perfluoroalkyl salts were refluxed in a liquid-liquid biphasic system (water/BTF) in the presence or absence of KI then 12 – 14 % of the phosphine oxide was formed. On the other hand, the butyl salt gave 9 % of the phosphine oxide in H₂O/BTF yet, on the addition of KI to this system, the butyl bis phosphine oxide was formed, 3 %, together with the phosphine oxide, 7 %.

In order to establish if the decomposition observed was a direct influence of the fluorinated ponytails, several non-fluorinated phosphonium salts were synthesised (Bu-PPh₃⁺Br⁻, Bn-PPh₃⁺Br⁻, Bu-PPh₃⁺CF₃SO₃⁻ and C₆F₁₃CH₂CH₂-PPh₃⁺CF₃SO₃⁻) and tested under identical conditions. The non-fluorinated phosphonium salts showed no evidence of decomposition to the phosphine, the phosphine oxide or the corresponding bis phosphine oxide. This indicates that the fluorinated-tagged phosphonium salts are more sensitive to decomposition due to the strong electron withdrawing effects of the fluorinated ponytails.

<i>Rf</i> -Catalyst	H ₂ O/BTF RT ^a	H ₂ O/KI/BTF RT ^a
[PhCH ₂ -P(4-C ₆ H ₄ C ₆ F ₁₃) ₃] ⁺ Br ⁻	P=O 2 %	P=O 2 %
[C ₆ F ₁₃ C ₂ H ₄ -P(4-C ₆ H ₄ C ₆ F ₁₃) ₃] ⁺ CF ₃ SO ₃ ⁻	P=O 6 %	P=O 6 %
[n-C ₄ H ₉ -P(4-C ₆ H ₄ C ₆ F ₁₃) ₃] ⁺ CF ₃ SO ₃ ⁻	P=O 5 %	P=O 7 %

^a P=O = P(O)(4-C₆H₄C₆F₁₃)₃

Table 26 Reactions carried out at room temperature

<i>Rf</i> -Catalyst	BTF Reflux ^a	H ₂ O/BTF Reflux ^a	H ₂ O/KI/ BTF Reflux ^a	BTF/KI Reflux ^a
[PhCH ₂ -P(4-C ₆ H ₄ C ₆ F ₁₃) ₃] ⁺ Br ⁻	P 5 % P=O 3 %	P 0 % P=O 2 %	P 0 % P=O 14 %	P 17 % P=O 10 %
[C ₆ F ₁₃ C ₂ H ₄ -P(4-C ₆ H ₄ C ₆ F ₁₃) ₃] ⁺ CF ₃ SO ₃ ⁻	P=O 0 %	P=O 14 %	P=O 12 %	P=O 7 %
[n-C ₄ H ₉ -P(4-C ₆ H ₄ C ₆ F ₁₃) ₃] ⁺ CF ₃ SO ₃ ⁻	P=O 0 %	P=O 9 %	BuP(O) 3 % P=O 7 %	P=O 6 %

^a P=O = P(O)(4-C₆H₄C₆F₁₃)₃, P = P(4-C₆H₄C₆F₁₃)₃, BuP(O) = Bu-P(O)(4-C₆H₄C₆F₁₃)₂

Table 27 Reactions carried out under reflux conditions

There are two possible routes for the decomposition of the benzyl phosphonium salt (Schemes 52 and 53). Route 1 (Scheme 52) shows the decomposition through a pentacovalent intermediate to give the phosphine oxide, whilst route 2 (Scheme 53) shows the formation of a Zwitterion via a phosphonium ylide pathway to give the same phosphine oxide.

detected by mass spectroscopy and ^{31}P NMR spectroscopy. Decomposition studies give evidence for the degradation of the fluorous-tagged phosphonium salts to the triaryl phosphine oxide which can be linked to the strong electron withdrawing effects of the perfluoroalkyl group.

3.9 References.

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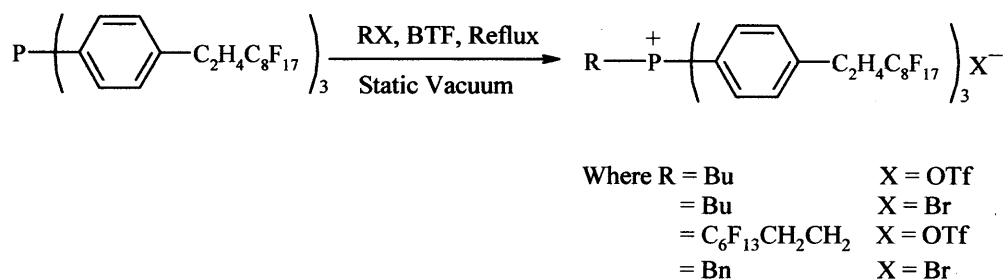
Chapter Four

4.0 Second Generation Fluorous-Tagged Phosphonium Salts.

4.1 Introduction.

The first generation of fluorous-tagged triaryl phosphonium salts proved to be unstable in phase transfer reactions because of the strong electron withdrawing effects of the fluorous ponytails. By incorporating an additional ethylene spacer unit (-CH₂CH₂) between the aryl ring and the fluorous ponytail (-C₈F₁₇), the phosphorus atom should be insulated from the electron withdrawing effects of the fluorous ponytail and hopefully, this should also enhance the stability of the phosphonium salts.

The aim of this chapter is to prepare a new series of fluorous-tagged phosphonium salts which contain an ethylene and aromatic spacer group (-C₆H₄CH₂CH₂) (Scheme 54). These new salts will be tested in picrate extractions and their extraction capabilities determined. Preliminary stability studies will also be carried out on the new fluorous-tagged phosphonium salts.

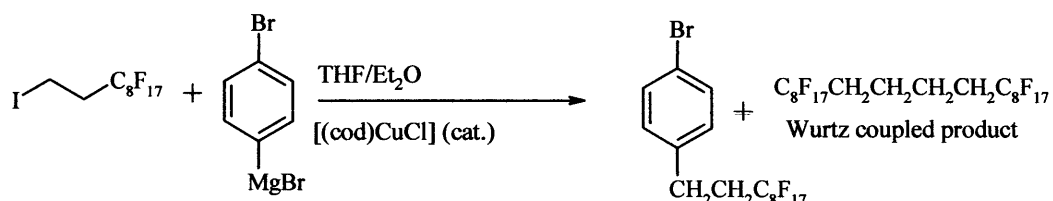


Scheme 54 Quaternisation reaction

4.2 Literature Methods for the Synthesis of Tris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl)phosphine.

The synthesis of tris(4-1*H*,1*H*,2*H*,2*H*-perfluoroalkylphenyl)phosphine has been carried out by four different routes. The key intermediate in three of the suggested routes is 4-(1*H*,1*H*,2*H*,2*H*-perfluorodecyl)bromobenzene. It is normally reacted with butyllithium to form the aryllithiate which is then reacted with PCl₃ to give tris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecyl)phosphine. Leitner attempted the synthesis of the tris(4-1*H*,1*H*,2*H*,2*H*-perfluoroalkylphenyl)phosphine by a copper catalysed coupling of the Grignard reagent, 4-BrC₆H₄MgBr, with 1*H*,1*H*,2*H*,2*H*-perfluorooctyl iodide to give 4-(1*H*,1*H*,2*H*,2*H*-

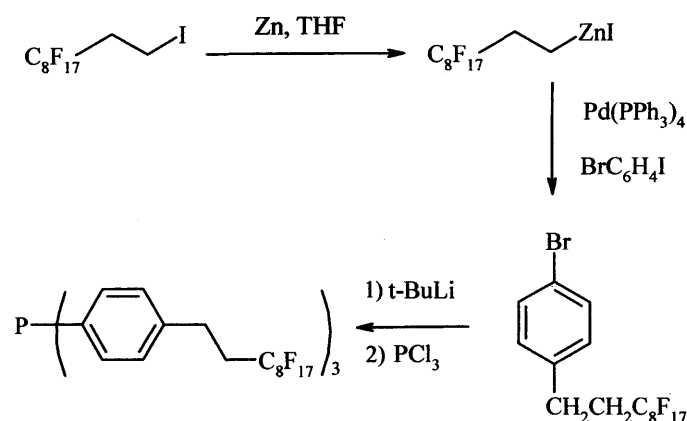
perfluorodecyl)bromobenzene. However, large amounts of the Wurtz coupled product were formed, $\text{C}_6\text{F}_{13}\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{C}_6\text{F}_{13}$ (Scheme 55).^{1,2} To remove the Wurtz coupled product, the crude material was distilled. Additional purification by conventional column chromatography proved difficult; instead, FRP silica gel was used, though poor yields of the perfluorinated bromoaromatic were obtained.³



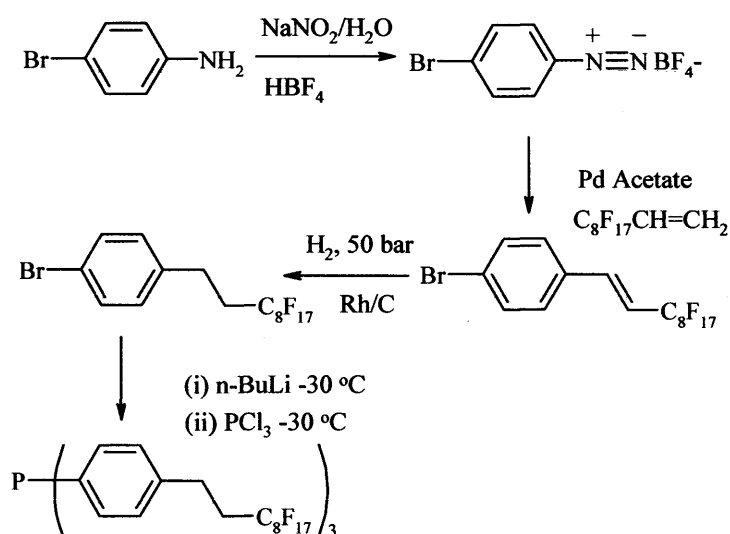
Scheme 55 Preparation of 4-(1*H*,1*H*,2*H*,2*H*-perfluorodecyl)bromobenzene

Another route for the synthesis of the triarylphosphine was developed by Curran who used the Pd-catalysed coupling of $\text{F}_{13}\text{C}_6\text{H}_4\text{CH}_2\text{CH}_2\text{ZnI}$ with 4-bromoiodobenzene to give 4-(1*H*,1*H*,2*H*,2*H*-perfluorodecyl)bromobenzene in good yields (Scheme 56).⁴ Genet developed an efficient Heck reaction between 1*H*,1*H*,2*H*-perfluoroalkenes and arenediazonium salts and the product was hydrogenated to give the perfluoroalkylated bromoaromatic.⁵ Finally, butyllithium was reacted with the perfluoroalkylated bromoaromatic to form the aryllithiate which was reacted with PCl_3 to give the triarylphosphine (Scheme 57).

The reaction of $\text{P}(\text{O})(4-\text{C}_6\text{H}_4\text{Br})_3$ with $\text{H}_2\text{C}=\text{CHC}_6\text{F}_{13}$ using a palladacycle offers the fluorine-tagged triarylphosphine oxide in 90 % yields. The triarylphosphine oxide was then reduced to the fluorine-tagged triarylphosphine using trichlorosilane.⁶



Scheme 56 Preparation of tris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl)phosphine



Scheme 57 Preparation of tris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl)phosphine

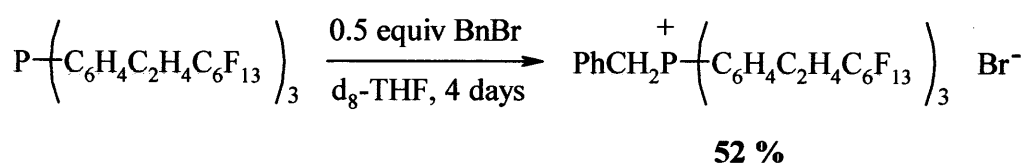
4.3 Synthesis of Tris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl)phosphine.

Genet's method for the synthesis of tris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl)phosphine was used. In order to synthesise the diazonium salt, sodium nitrite was added slowly to 4-bromoaniline at 5 °C (Scheme 57).⁵ The next step was the Heck reaction between the diazonium salt and 1*H*,1*H*,2*H*,2*H*-perfluorodec-1-ene to give the perfluorinated bromoaromatic. Both steps were high yielding and the overall purity was greater than 95 %. The double bond was then reduced by a room temperature hydrogenation catalysed by rhodium on carbon for 24 hours to give the desired product in 82 % yield. The aryllithiate

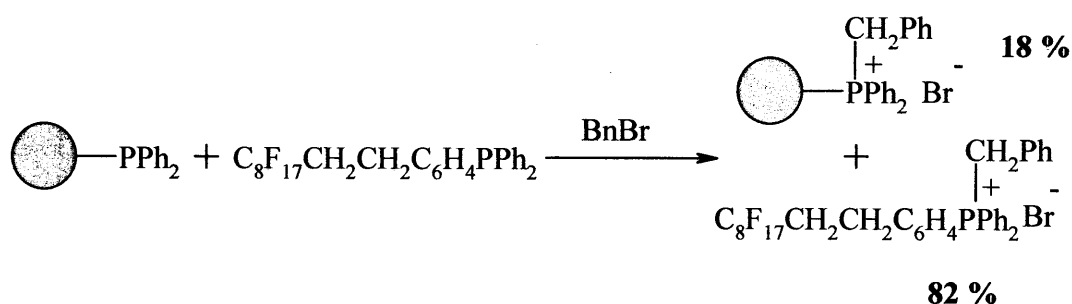
was formed by the reaction of (4-1*H*,1*H*,2*H*,2*H*-perfluorodecyl)bromo-benzene with *n*-BuLi and was subsequently reacted with PCl₃. Unfortunately, (4-1*H*,1*H*,2*H*,2*H*-perfluorodecyl)bromobenzene is not very soluble in diethyl ether at low temperatures and so the reaction was carried out in two different solvent systems: 1) in dilute solutions of diethyl ether; 2) a diethyl ether/THF (1:1) mix. In general, after the addition of the *n*-BuLi at -40 °C, the reaction mixture was allowed to warm to -30 °C for 2 hours to ensure complete lithiation for both procedures. The solvent system containing only diethyl ether was found to give better yields.

4.4 Literature Methods for the Preparation of Perfluorinated Phosphonium Salts.

There is only one key report on the synthesis of triaryl perfluorinated phosphonium salts that contain the spacer group, -CH₂CH₂, between the fluorine ponytails and the aromatic ring.⁷ Curran compared the reactivity of triphenylphosphine and fluorine phosphines of heavy, medium and light fluorine content in several reactions. One reaction was the alkylation of the phosphines to form the phosphonium salt as shown in Scheme 58. The syntheses of these salts was carried out by the reaction of several perfluorinated phosphines with BnBr in d₈-THF in good yields, 52 – 62 % (Scheme 58). Competitive reactions were also carried out between fluorine phosphines and resin bound phosphines (Scheme 59) to form the phosphonium salt.



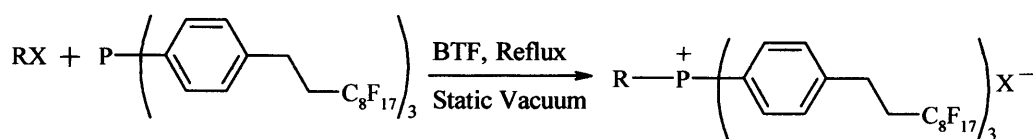
Scheme 58 Synthesis of phosphonium salt



Scheme 59 Competitive reactions

4.5 Quaternisation of Tris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl)phosphine.

A series of perfluoroalkylated triarylphosphonium salts containing a $-\text{CH}_2\text{CH}_2$ spacer group placed between the fluoros ponytails and the aryl ring have been synthesised by the quaternisation of tris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl)phosphine, $\text{P}(4\text{-C}_6\text{H}_4\text{CH}_2\text{CH}_2\text{C}_8\text{F}_{17})_3$ (Scheme 60). The butyl triaryl spacer phosphonium salt, $[\text{n-C}_4\text{H}_9\text{-P}(4\text{-C}_6\text{H}_4\text{CH}_2\text{CH}_2\text{C}_8\text{F}_{17})_3]^+\text{Br}^-$, was synthesised by refluxing the triarylphosphine with an excess of butyl bromide and complete conversion was obtained after 72 hours (by ^{31}P NMR spectroscopy). In contrast, it was not possible to quaternise the first generation triaryl phosphine, $\text{P}(4\text{-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3$ with butyl bromide demonstrating that the two methylene spacer groups between the aromatic ring and the perfluoroalkyl group are essential for insulating the phosphorus donor atom from the strong electron withdrawing effects of the fluoros ponytails (Table 28). Three further salts were prepared by the reaction of tris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl)phosphine with an excess of either 1*H*,1*H*,2*H*,2*H*-perfluorooctyl triflate, butyl triflate or benzyl bromide. All of these reactions were monitored by ^{31}P NMR spectroscopy and were complete in 1-3 hours in direct contrast with the much longer reaction times that were required for the quaternisation of $\text{P}(4\text{-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3$ (Table 29). Again, this demonstrates the much greater efficiency of the 4- $\text{C}_6\text{H}_4\text{C}_2\text{H}_4$ hydrocarbon spacer group compared to the 4- C_6H_4 aromatic spacer group.



Scheme 60 Quaternisation reaction

R group	X, anion	Temp (°C)	Time (h)	Yield (%)
PhCH ₂	Br	110	0.5	53
C ₆ F ₁₃ C ₂ H ₄	CF ₃ SO ₃	80	1	83
C ₄ H ₉	CF ₃ SO ₃	45	3	45
C ₄ H ₉	Br	110	72	64

Table 28 Synthesis of fluoros phosphonium salts

Phosphine	BnBr	BuBr	BuOTf	RfC ₂ H ₄ OTf
P(ArRf ₆) ₃	32 hours	5.5 days ^a	48 hours	96 hours
P(ArC ₂ H ₄ Rf ₈) ₃	30 mins	3 days	3 hours	1 hour

^aOnly 6 % conversion obtained

Table 29 Comparison of reaction times

The conversions of the triaryl spacer phosphine to the benzyl and butyl phosphonium spacer salts are extremely quick and clean reactions. Quantitative conversion to the four fluororous ponytail phosphonium salt was also found to be a quick reaction but showed an additional peak in the ³¹P NMR spectrum (δ_P 65.44). The salt was purified by distillation to remove the excess triflate followed by aqueous work up which proved effective in the removal of the anomalous phosphorus species. All of these salts were obtained as viscous oils which were triturated in hexane for several days before a final wash with hexane/diethyl ether (1:1, 10 cm³) was carried out.

As expected, the ³¹P NMR signals were shifted downfield (δ_P 23.4 – 24.4 ppm). The ¹³C{¹H} NMR spectra showed that the PCH signals were coupled to phosphorus (δ_C 116.3 – 116.7, ¹J_{CP} = 87.5 – 88.6 Hz) and the CH₂CF₂ signals were coupled to fluorine (δ_C 31.3, ²J_{CF} = 21.5 – 22.1 Hz) (Table 30). The mass spectra proved to be invaluable as they showed peaks for both the cations and anions. The fluororous phosphonium salts melted in the range of room temperature to 145 °C, with two of the salts remaining as very viscous oils showing their potential to be used as a novel fluororous ionic liquids.

Salt	δ_P (ppm)	Mp ($^{\circ}\text{C}$)	PC δ_C (ppm) Shifts and Coupling Constants.	ArCH ₂ CF ₂ δ_C (ppm) shifts and Coupling Constants
Bn- P(ArC ₂ H ₄ Rf) ₃ Br	23.5	138 – 145	116.7 (d, $^1J_{CP}$ = 87.5 Hz)	31.4 (t, $^2J_{CF}$ = 21.6 Hz)
Bu- P(ArC ₂ H ₄ Rf) ₃ Br	23.6	98 - 102	116.3 (d, $^1J_{CP}$ = 87.5 Hz)	31.4 (t, $^2J_{CF}$ = 21.5 Hz)
C ₆ F ₁₃ C ₂ H ₄ P(ArC ₂ H ₄ Rf) ₃ OTf	24.4	viscous oil	115.4 (d, $^1J_{CP}$ = 88.6 Hz)	31.3 (t, $^2J_{CF}$ = 22.1 Hz)
Bu- P(ArC ₂ H ₄ Rf) ₃ OTf	23.4	oil	116.7 (d, $^1J_{CP}$ = 87.5 Hz)	31.3 (t, $^2J_{CF}$ = 21.6 Hz)

Table 30 NMR data of 2nd generation phosphonium salts

4.6 Picrate Extractions.

The extraction of the picrate anion from the aqueous phase into the organic phase was examined for each of the 2nd generation fluororous tagged triaryl spacer phosphonium salts and the results are compared directly with the standard phase transfer catalysts, tetrabutyl-*n*-ammonium bromide (TBAB) and benzyl triphenylphosphonium bromide. The information obtained will show the different extraction capabilities of each phosphonium salt as well as providing evidence that each salt is acting as a phase transfer catalyst. Each of the reactions was carried out three times and good reproducibility was obtained in all cases (Tables 31 and 32).

The results obtained for the second generation fluororous-tagged phosphonium salts in the picrate extractions are extremely good. It can be seen that the non-fluorinated phosphonium salt, PhCH₂-PPh₃⁺Br⁻, and the benzyl triaryl spacer phosphonium salt, PhCH₂-P(4-C₆H₄CH₂CH₂C₈F₁₇)₃⁺Br⁻, are very similar and give good extraction of the picrate to the organic phase, 94 % and 96 % respectively. Overall, the following series for the fluororous-tagged spacer phosphonium salts can be established: PhCH₂-P(4-C₆H₄CH₂CH₂C₈F₁₇)₃⁺Br⁻ > *n*-C₄H₉-P(4-C₆H₄CH₂CH₂C₈F₁₇)₃⁺CF₃SO₃⁻ > C₆F₁₃CH₂CH₂-P(4-C₆H₄CH₂CH₂C₈F₁₇)₃⁺CF₃SO₃⁻ > *n*-C₄H₉-P(4-C₆H₄CH₂CH₂C₈F₁₇)₃⁺Br⁻. Both C₄H₉-P(4-

$\text{C}_6\text{H}_4\text{CH}_2\text{CH}_2\text{C}_8\text{F}_{17})_3^+\text{CF}_3\text{SO}_3^-$ and $n\text{-C}_4\text{H}_9\text{-P}(4\text{-C}_6\text{H}_4\text{CH}_2\text{CH}_2\text{C}_8\text{F}_{17})_3^+\text{Br}^-$ give very good extraction of the picrate to the organic phase, 87 % and 76 % respectively. However, it is evident that the triflate anion is acting as a better leaving group compared to the bromide anion.

<i>F-Salt Tested</i>	Abs. of <i>Aq</i> Phase	% Ext to Org Phase	Average
PhCH ₂ -P(ArCH ₂ CH ₂ Rf) ₃ ⁺ Br ⁻	0.093	93.6	95.9 % ± 2.0
PhCH ₂ -P(ArCH ₂ CH ₂ Rf) ₃ ⁺ Br ⁻	0.043	97.1	
PhCH ₂ -P(ArCH ₂ CH ₂ Rf) ₃ ⁺ Br ⁻	0.045	97.0	
Blank	1.459	0.0	
RfC ₂ H ₄ - P(ArCH ₂ CH ₂ Rf) ⁺ CF ₃ SO ₃ ⁻	0.235	83.5	85.3 % ± 1.9
RfC ₂ H ₄ - P(ArCH ₂ CH ₂ Rf) ⁺ CF ₃ SO ₃ ⁻	0.225	84.4	
RfC ₂ H ₄ - P(ArCH ₂ CH ₂ Rf) ⁺ CF ₃ SO ₃ ⁻	0.171	87.9	
Blank	1.431	0.0	
C ₄ H ₉ - P(ArCH ₂ CH ₂ Rf) ⁺ CF ₃ SO ₃ ⁻	0.349	75.4	76.6 % ± 3.3
C ₄ H ₉ - P(ArCH ₂ CH ₂ Rf) ⁺ CF ₃ SO ₃ ⁻	0.279	80.4	
C ₄ H ₉ - P(ArCH ₂ CH ₂ Rf) ⁺ CF ₃ SO ₃ ⁻	0.371	73.9	
Blank	1.421	0.0	
C ₄ H ₉ -PPh ₃ ⁺ CF ₃ SO ₃ ⁻	0.162	88.6	87.2 % ± 1.3
C ₄ H ₉ -PPh ₃ ⁺ CF ₃ SO ₃ ⁻	0.199	86.0	
C ₄ H ₉ -PPh ₃ ⁺ CF ₃ SO ₃ ⁻	0.183	87.1	
Blank	1.420	0.0	
PhCH ₂ -PPh ₃ ⁺ Br ⁻	0.099	93.7	94.4 % ± 0.6
PhCH ₂ -PPh ₃ ⁺ Br ⁻	0.079	95.0	
PhCH ₂ -PPh ₃ ⁺ Br ⁻	0.087	94.5	
Blank	1.573	0.0	

Table 31 Picrate extractions (1:1 ratio of picrate to salt) of 2nd generation phosphonium salts

<i>F-Salt Tested</i>	Abs. of <i>Aq</i> Phase	% Ext to Org Phase	Average
PhCH ₂ -P(ArCH ₂ CH ₂ Rf) ₃ ⁺ Br ⁻	0.742	49.1	47.4 ± 1.5
PhCH ₂ -P(ArCH ₂ CH ₂ Rf) ₃ ⁺ Br ⁻	0.784	46.3	
PhCH ₂ -P(ArCH ₂ CH ₂ Rf) ₃ ⁺ Br ⁻	0.774	46.8	
Blank	1.459	0.0	
RfC ₂ H ₄ - P(ArCH ₂ CH ₂ Rf) ₃ ⁺ CF ₃ SO ₃ ⁻	0.831	48.9	42.9 ± 0.7
RfC ₂ H ₄ - P(ArCH ₂ CH ₂ Rf) ₃ ⁺ CF ₃ SO ₃ ⁻	0.894	50.0	
RfC ₂ H ₄ - P(ArCH ₂ CH ₂ Rf) ₃ ⁺ CF ₃ SO ₃ ⁻	0.834	48.7	
Blank	1.431	0.0	
C ₄ H ₉ - P(ArCH ₂ CH ₂ Rf) ₃ ⁺ CF ₃ SO ₃ ⁻	0.884	37.8	39.4 ± 2.1
C ₄ H ₉ - P(ArCH ₂ CH ₂ Rf) ₃ ⁺ CF ₃ SO ₃ ⁻	0.829	41.7	
C ₄ H ₉ - P(ArCH ₂ CH ₂ Rf) ₃ ⁺ CF ₃ SO ₃ ⁻	0.872	38.6	
Blank	1.421	0.0	
C ₄ H ₉ -PPh ₃ ⁺ CF ₃ SO ₃ ⁻	0.814	42.7	43.5 ± 0.9
C ₄ H ₉ -PPh ₃ ⁺ CF ₃ SO ₃ ⁻	0.790	44.4	
C ₄ H ₉ -PPh ₃ ⁺ CF ₃ SO ₃ ⁻	0.804	43.4	
Blank	1.420	0.0	
PhCH ₂ -PPh ₃ ⁺ Br ⁻	0.739	53.0	52 % ± 6.4
PhCH ₂ -PPh ₃ ⁺ Br ⁻	0.887	44.0	
PhCH ₂ -PPh ₃ ⁺ Br ⁻	0.759	52.0	
Blank	1.581	0.0	

Table 32 Picrate extractions (2:1 ratio of picrate to salt) of 2nd generation phosphonium salts

The picrate extractions of the 1st generation triaryl phosphonium salts and the 2nd generation triaryl spacer phosphonium salts are summarised in Table 33. It is apparent that the results obtained for the 2nd generation spacer phosphonium salts are slightly lower than the 1st generation phosphonium salts. This is clearly seen by the benzyl and alkyl spacer phosphonium salts. However, the butyl spacer phosphonium salt gave a very similar result, 87.2 %, compared to the analogous 1st generation phosphonium salt, 84.6 %.

Fluorous salt	Extraction into The Organic Phase (%) (1:1 ratio of picrate to salt)	Extraction into The Organic Phase (%) (2:1 ratio of picrate to salt)
Bn-P(ArRf) ₃ Br	100.0	50.0
Bn-P(ArC ₂ H ₄ Rf) ₃ Br	95.9	47.4
Bu-P(ArRf) ₃ OTf	84.6	40.5
Bu-P(ArC ₂ H ₄ Rf) ₃ OTf	87.2	43.5
C ₆ F ₁₃ C ₂ H ₄ -P(ArRf) ₃ OTf	95.9	46.3
C ₆ F ₁₃ C ₂ H ₄ -P(ArC ₂ H ₄ Rf) ₃ OTf	85.3	42.9
Bu-P(ArC ₂ H ₄ Rf) ₃ Br	76.6	39.4

Table 33 Comparison of 1st and 2nd generation phosphonium salts in picrate extractions

4.7 Preliminary Stability Studies.

Preliminary work was carried out to investigate the stability of the 2nd generation phosphonium salts. It was proposed that a -CH₂CH₂ spacer group between the aromatic ring and the perfluoroalkyl ponytail would reduce the electron withdrawing effect of the fluorous ponytails and, hopefully prevent the decomposition to the fluorous triaryl phosphine oxide.

Only the 2nd generation benzyl salt was tested since the analogous 1st generation salt proved to be more sensitive to decomposition than the other salts. Table 34 summarizes the results under room temperature and refluxing (110 °C) conditions. Although 6-7 % of triarylphosphine oxide was already present in the fluorous phosphonium salt, the values

obtained after the stability test are within experimental error using integration in the ^1H NMR spectrum. The fluoros phosphonium salt containing the additional ethylene spacer group therefore proved to be much more stable compared to the 1st generation salt, $\text{PhCH}_2\text{-P(4-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3^+\text{Br}^-$.

Conditions	$\text{H}_2\text{O/BTF/RT}^a$	$\text{H}_2\text{O/BTF/KI/RT}^a$	BTF/Reflux^a	$\text{H}_2\text{O/BTF/Reflux}^a$	$\text{H}_2\text{O/KI/BTF/Reflux}^a$	BTF/KI/Reflux^a
Phosphine Oxide (%)	9 %	8 %	8 %	6 %	5 %	6 %

^a Phosphine oxide already present in fluoros salt before stability studies = 7 %

Table 34 Stability studies of $[\text{PhCH}_2\text{-P(4-C}_6\text{H}_4\text{CH}_2\text{CH}_2\text{C}_8\text{F}_{17})_3]^+\text{Br}^-$

4.8 Conclusions.

A series of 2nd generation fluoros phosphonium salts were successfully prepared that contain two methylene ($-\text{CH}_2\text{CH}_2$) spacer groups between the fluoros ponytail and the aromatic ring. The quaternisation process was monitored by ^{31}P NMR spectroscopy and the rate of quaternisation was compared to the 1st generation salts. For example, the preparation of $\text{Bu-P(4-C}_6\text{H}_4\text{CH}_2\text{CH}_2\text{C}_8\text{F}_{17})_3^+\text{Br}^-$, was prepared in 72 hours with good conversions, 54 %, whereas the $\text{Bu-P(4-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3^+\text{Br}^-$ was only obtained in 6 % conversion after 132 hours. Picrate extractions were carried out and showed highly effective anion transfer under liquid-liquid conditions compared to standard phosphonium salts. Preliminary stability studies also revealed that the benzyl salt, $\text{PhCH}_2\text{-P(4-C}_6\text{H}_4\text{CH}_2\text{CH}_2\text{C}_8\text{F}_{17})_3^+\text{Br}^-$, did not decompose to the phosphine oxide even under refluxing conditions. The stability of the 2nd generation fluoros phosphonium salt is superior because of the presence of the $-\text{CH}_2\text{CH}_2$ group which insulates the phosphine from the electron withdrawing effects of the fluoros ponytails.

4.9 References.

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Chapter 5

5.0 Experimental Section

5.1 General Procedures.

5.1.1 Nuclear Magnetic Resonance Spectroscopy.

^1H , ^{31}P , $^1\text{H}\{^{31}\text{P}\}$, $^{19}\text{F}\{^1\text{H}\}$ and $^{13}\text{C}\{^1\text{H}\}$ spectra were all recorded on a Bruker DRX 400, Bruker AM 300 and Bruker ARX 250 spectrometers at ambient temperatures unless otherwise stated. ^1H and $^{13}\text{C}\{^1\text{H}\}$ NMR spectra were referenced internally using the residual *protio* solvent resonance relative to SiMe_4 ($\delta_{\text{H}} = 0$ ppm) and CDCl_3 ($\delta_{\text{C}} = 77.0$ ppm), whilst ^{19}F NMR spectra were referenced to external CFCl_3 ($\delta_{\text{F}} = 0$ ppm) and ^{31}P NMR spectra were referenced externally to 85 % H_3PO_4 ($\delta_{\text{P}} = 0$ ppm). All chemical shifts are quoted in δ (ppm) and coupling constants in Hertz (Hz), using the high frequency positive convention. The highly coupled ^{13}C signals of the fluorinated carbons are not listed below. The spectrometer frequencies are given in the following table:

Spectrometer	^1H Frequency (MHz)	^{19}F Frequency (MHz)	^{31}P Frequency (MHz)	^{13}C Frequency (MHz)
Bruker ARX 250	250.13	235.34	101.26	62.90
Bruker AM 300	300.14	282.41	121.80	75.47
Bruker DRX 400	400.13	376.46	161.97	100.61

The solvent most commonly used was deuterated chloroform (CDCl_3). However, if this was not possible due to solubility problems, an alternative deuterated solvent was used. Failing this a common laboratory solvent such as diethyl ether was used and a lock tube (capillary insert tube containing C_6D_6) was inserted. Air/moisture sensitive compounds were prepared under an inert atmosphere using a dry-box as well as previously dried and freeze/pumped/thawed/degassed deuterated solvents. The solutions were then loaded into either a Young's NMR tube or a Teflon-sealed screw-cap NMR tube.

5.1.2 Mass Spectrometry.

Electron impact (EI) and fast atom bombardment (FAB) mass spectra were recorded on a Kratos concept 1H, double focusing, forward geometry mass spectrometer. 3-Nitrobenzyl alcohol was used as the matrix for the FAB spectra. Electrospray (ES) mass spectra were obtained on a Micromass Quatro LC spectrometer.

5.1.3 Anhydrous Solvents.

Unless otherwise stated, all the dried solvents were freeze/pumped/thawed/degassed before use:-

Solvent	Drying
<ul style="list-style-type: none">• Diethyl Ether• Hexane• Tetrahydrofuran• Toluene	Dried by refluxing over sodium metal and benzophenone under an atmosphere of dry nitrogen for three days. Distilled under nitrogen and stored in a closed ampoule containing activated 4 Å molecular sieves that had been heated under vacuum at 200 °C for three days.
<ul style="list-style-type: none">• Dichloromethane• PP3	Dried by refluxed over calcium hydride under a nitrogen atmosphere for three days. Distilled under nitrogen and stored in a closed ampoule containing activated 4 Å molecular sieves that had been heated under vacuum at 200 °C for three days.
<ul style="list-style-type: none">• 1,1,1-Trifluorotoluene (BTF)• Octafluorotoluene (F₈-Toluene)	Refluxed over phosphorus pentoxide under a nitrogen atmosphere for three days. Distilled under nitrogen and then stored in a closed ampoule containing activated 4 Å molecular sieves that had been heated under vacuum at 200 °C for three days.

5.1.4 Elemental Analysis.

Elemental analyses were performed by the University of North London and Butterworth Laboratories.

5.1.5 Laboratory Apparatus.

Schlenk Line.



The manipulation of air and moisture sensitive compounds was carried out using standard Schlenk techniques. The apparatus consisted of a glass dual manifold line connected to both a nitrogen supply and a vacuum pump which was protected by a liquid nitrogen trap. The reaction vessels were connected to the line by thick wall neoprene vacuum tubing with the nitrogen/vacuum supplies controlled by a ground glass tap.

Glassware and Multireactors.



Phase transfer catalysed reactions were carried out using an Electrotherm carousel station in which the reaction tubes could be evacuated and backfilled with nitrogen three times prior to use. The majority of reactions were carried out in Pyrex glassware with Quickfit joints. Young's flasks were used for the preparation of all fluorine-tagged phosphonium salts.

Faircrest Dry-box and Nitrogen Flush-box.

The transfer of air and moisture sensitive compounds was carried out in either a Faircrest auto-recirculating positive pressure dry-box or a nitrogen positive pressure flush box. The nitrogen atmosphere of the Faircrest dry-box was maintained *via* circulating through columns of molecular sieves and manganese dioxide that removed water and oxygen (< 5 ppm) respectively. A positive flow of dry nitrogen and an activated molecular sieve filter maintained the atmosphere of the nitrogen flush-box.

5.1.6 Gas Chromatography.

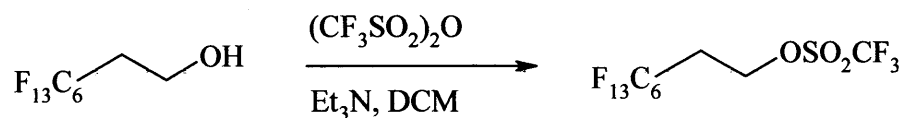
At Avecia (*Huddersfield*) a Hewlett Packard gc was used with a Varian (Chrompac) CP-Sil 8 CB (25m x 32 μ m x 0.12 μ m) column. At Leicester University a Clarus 500 Perkin Elmer gc was used with a Varian (Chrompac) CP-Sil 8 CB (25m x 32 μ m x 0.12 μ m) column.

5.1.7 Starting Materials.

All starting reagents were generally purchased from Sigma-Aldrich, Apollo Scientific, Lancaster or Fluorochem. 1*H*,1*H*,2*H*,2*H*-perfluorooctyl iodide and butan-1-ol were distilled prior to use. PCl₃ was distilled and stored under nitrogen. Triethylamine and pyridine were dried by refluxing over calcium hydride followed by distillation. Aqueous ammonium chloride was degassed by bubbling nitrogen through for 20 minutes before placing the solution under vacuum and back filling with nitrogen, three times.

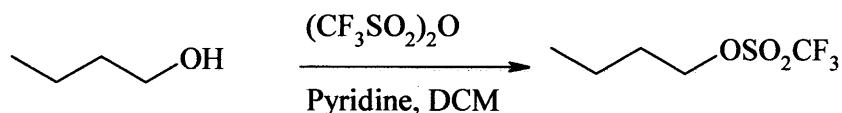
5.2 Experimental Details for Chapter Two.

Preparation of 1*H*,1*H*,2*H*,2*H*-perfluorooctyltrifluoromethane sulfonate.



The preparation of 1*H*,1*H*,2*H*,2*H*-perfluorooctyltrifluoromethane sulfonate was carried out by an adaption of Kvičala's method.¹ A solution of 1*H*,1*H*,2*H*,2*H*-perfluorooctan-1-ol (8.81 g, 5.24 cm³, 24 mmol), triethylamine (2.45 g, 3.37 cm³, 24 mmol) and dichloromethane (20 cm³) was added over 1 hour to trifluoromethanesulfonic anhydride (9.37 g, 5.59 cm³, 33 mmol) stirring at -5 °C in dichloromethane (60 cm³) under nitrogen. After stirring the reaction mixture for a further hour at -5 °C, it was warmed to room temperature over 30 minutes and stirred for a further 30 minutes at room temperature. The reaction mixture was extracted with PP3 (2 x 50 cm³). The PP3 layers were combined, washed with water (3 x 100 cm³), dried (MgSO₄) and the solvent removed on the rotary evaporator to give F₁₃C₆CH₂CH₂OSO₂CF₃ as a clear oil (8.00 g, 85 %). δ_{H} (250.13 MHz) 2.58 (2H, tt, $^3J_{\text{HF}}$ 17.4, $^3J_{\text{HH}}$ 6.3, CH₂C₆F₁₃), 4.68 (2H, t, $^3J_{\text{HH}}$ 6.3, CH₂OSO₂CF₃); δ_{F} (235.34 MHz) -75.45 (3F, s, OSO₂CF₃), -81.68 (3F, t, $^4J_{\text{FF}}$ 9.9, CF₃), -114.26 (2F, t, $^4J_{\text{FF}}$ 12.6, α -CF₂), -122.51 (2F, m, CF₂), -123.55 (2F, m, CF₂), -124.15 (2F, m, CF₂), -126.88 (2F, m, CF₂); δ_{C} (62.90 MHz) 31.20 (t, $^2J_{\text{CF}}$ 21.9, CH₂), 67.51 (CH₂); m/z (EI) 427 (M⁺ - CF₃, 80%).

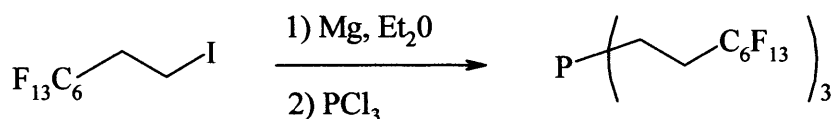
Preparation of *n*-butyltrifluoromethane sulfonate.



A solution of *n*-butanol (3.65 g, 4.45 cm³, 49 mmol), pyridine (4.0 cm³, 49 mmol) and dichloromethane (30 cm³) was added over a period of 45 minutes to trifluoromethanesulfonic anhydride (10.9 cm³, 64 mmol) stirring at -5 °C in dichloromethane (60 cm³) under nitrogen. After stirring the reaction mixture for a further

45 minutes at 0 °C, the solution was warmed to room temperature over 30 minutes and stirred for a further 30 minutes at room temperature. An exotherm was observed when water (80 cm³) was added slowly to quench the reaction. The organic layer was then separated, washed with water (2 x 50 cm³), dried with MgSO₄ and the solvent was removed on the rotary evaporator. The product was purified by Kugelröhr distillation (bp 45 - 50 °C at 29.7 mbar) to give butyl triflate as a clear oil (6.70 g, 66 %). δ_{H} (250.13 MHz) 0.88 (3H, t, $^3J_{\text{HH}}$ 7.3, CH₃), 1.38 (2H, sextet, $^3J_{\text{HH}}$ 7.4, CH₂CH₃), 1.73 (2H, m, OCH₂CH₂), 4.46 (2H, t, $^3J_{\text{HH}}$ 7.4, OCH₂); δ_{F} (235.34 MHz) -75.60 (3F, s, OSO₂CF₃); δ_{C} (62.90 MHz) 13.19 (CH₃), 18.28 (CH₂), 30.32 (CH₂), 77.48 (CH₂); m/z (EI) 137 (M⁺ - CF₃, 100 %).

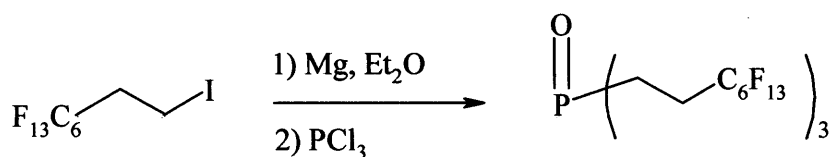
Preparation of tris(1*H*,1*H*,2*H*,2*H*-perfluorooctyl)phosphine.



The preparation of tris(1*H*,1*H*,2*H*,2*H*-perfluorooctyl)phosphine was carried out following Hope's method.² A solution of 1*H*,1*H*,2*H*,2*H*-perfluorooctyl iodide (24.46 g, 52.0 mmol) and 1,2-dibromoethane (1.0 cm³, 11.6 mmol) in diethyl ether (50 cm³) was added drop wise to magnesium turnings (1.67 g, 69.0 mmol) suspended in diethyl ether (70 cm³) over 45 minutes whilst maintaining a temperature of 30 °C under nitrogen. Once all the 1*H*,1*H*,2*H*,2*H*-perfluorooctyl iodide had been added, the mixture was refluxed for three hours. After cooling the reaction mixture to room temperature, the solution was filtered through a canula needle under nitrogen in order to remove the excess magnesium. A solution of PCl₃ (0.75 cm³, 8.6 mmol) in diethyl ether (50 cm³) was added over a period of two hours at room temperature and the mixture was stirred overnight. The mixture was hydrolysed with a 10 % degassed aqueous ammonium chloride (100 cm³) solution and the organic layer separated, dried with MgSO₄ and the solvent was removed *in vacuo* to obtain a viscous orange oil. The resulting orange oil was heated under dynamic vacuum to remove all traces of C₆F₁₃CH₂CH₂CH₂CH₂C₆F₁₃ (bp 50 - 60 °C at 0.01 mmHg) (0.93 g, 8 %). δ_{H} (d₆-acetone, 250.13 MHz) 1.65 (2H, m, CH₂CH₂C₆F₁₃), 2.05 (2H, br t, $^3J_{\text{HF}}$ 18.4, CH₂CH₂C₆F₁₃); δ_{F} (235.34 MHz) -81.29 (6F, t, $^4J_{\text{FF}}$ 10.6, CF₃), -114.82 (4F, m, α -CF₂), -122.37 (4F, m, CF₂), -122.99 (4F, m, CF₂), -123.34 (4F, m, CF₂), -126.59 (4F, m, CF₂); δ_{C} (62.90 MHz) 19.90 (CH₂), 30.62 (t, $^2J_{\text{CF}}$ 22.8, CH₂). The product was distilled to give pure

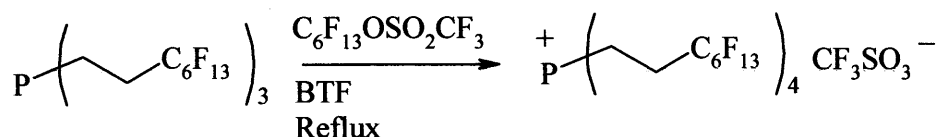
tris(1*H*,1*H*,2*H*,2*H*-perfluorooctyl)phosphine (bp 175 - 200 °C at 0.01 mmHg) as a colourless liquid (3.88 g, 42 %). δ_{H} 1.66 (2H, m, CH₂C₆F₁₃), 2.11 (2H, m, CH₂P); δ_{F} -81.44 (9F, t, $^4J_{\text{FF}}$ 9.3, CF₃), -115.37 (6F, t, $^4J_{\text{FF}}$ 13.3, α -CF₂), -122.43 (6F, m, CF₂), -123.42 (6F, m, CF₂), -123.84 (6F, m, CF₂), -126.70 (6F, m, CF₂); δ_{P} (101.26 MHz) -25.74 (s); δ_{C} (400 MHz) 15.95 (d, J_{CP} 15.6, CH₂), 27.66 (td, $^2J_{\text{CF}}$ 22.5, J_{CP} 19.1, CH₂).

Preparation of tris(1*H*,1*H*,2*H*,2*H*-perfluorooctyl)phosphine oxide.



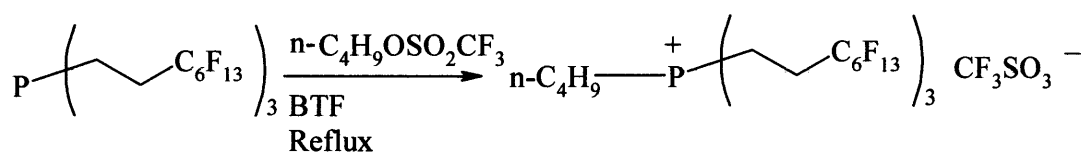
A solution of 1*H*,1*H*,2*H*,2*H*-perfluorooctyl iodide (16.16 g, 34.0 mol) in diethyl ether (50 cm³) was added drop wise to magnesium turnings (1.67 g, 69.0 mol) suspended in diethyl ether (70 cm³) with one to two drops of 1,2-dibromoethane under nitrogen. Once all the 1*H*,1*H*,2*H*,2*H*-perfluorooctyl iodide had been added, the mixture was refluxed for three hours. After cooling the reaction mixture to room temperature, the solution was filtered through a canula needle under nitrogen in order to remove the excess magnesium. A solution of phosphorus trichloride (0.75 cm³, 8.6 mmol) in diethyl ether (50 cm³) was added over a period of two hours at room temperature and the mixture was stirred overnight. The mixture was hydrolysed with 10 % degassed aqueous ammonium chloride (100 cm³) solution and the organic layer was separated and dried with MgSO₄ in air. The solvent was removed on the rotary evaporator and the orange solid was distilled under vacuum to afford the phosphine oxide (bp 175 - 200 °C at 0.01 mmHg) as a white solid (0.77 g, 2.1 %). δ_{H} (d₆-acetone, 250.13 MHz) 2.00 (2H, m, CH₂C₆F₁₃), 2.40 (2H, m, CH₂P); δ_{F} (235.34) -81.27 (9F, t, $^4J_{\text{FF}}$ 9.3, CF₃), -115.29 (6F, t, $^4J_{\text{FF}}$ 10.6, α -CF₂), -122.27 (6F, m, CF₂), -123.30 (6F, m, CF₂), -123.56 (6F, m, CF₂), -126.59 (6F, m, CF₂); δ_{P} (101.26 MHz) 42.80 (s); δ_{C} (62.90 MHz) 20.28 (d, J_{CP} 19.7, CH₂), 24.42 (t, $^2J_{\text{CF}}$ 21.5, CH₂); *m/z* (FAB) 1089 (MH⁺, 100%).

Preparation of tetra(1*H*,1*H*,2*H*,2*H*-perfluorooctyl)phosphonium trifluoromethane sulfonate.



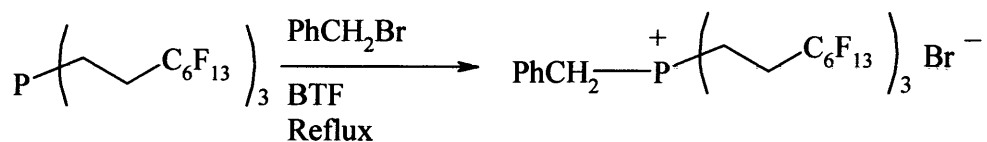
A small ampoule was flamed dried, back filled with nitrogen and charged with tris(1*H*,1*H*,2*H*,2*H*-perfluorooctyl)phosphine (2.00 g, 1.87 mmol), 1*H*,1*H*,2*H*,2*H*-perfluorooctyltriflate (4.43 g, 8.93 mmol), and benzotrifluoride (10 cm³) and then freeze/pumped/thawed/degassed to remove any dissolved gases. The reaction mixture was heated to 80 °C under static vacuum for 37 h. After cooling the reaction mixture to room temperature, it was back filled with nitrogen and the solvent removed on the rotary evaporator to give a viscous oil. The viscous oil was then triturated with hexane (2 x 15 cm³) and then toluene (15 cm³). This was repeated five times before placing the salt under oil pump vacuum for a day to give a foam type appearance. A final wash with diethyl ether (10 cm³) removed any phosphine oxide and the salt was finally dried under vacuum to yield a white powder (1.19 g, 41 %). mp 82 – 84 °C; (Found: C, 25.3; H, 1.0; P, 2.5; S, 2.1, C₃₃H₁₆F₅₅O₃PS requires C, 25.3; H, 1.0; P, 2.0; S, 2.0 %); δ_{H} (d₆-acetone, 300.14 MHz) 3.11 (2H, m, CH₂C₆F₁₃), 3.37 (2H, m, PCH₂); δ_{F} (376.46 MHz) -78.22 (3F, s, OSO₂CF₃), -80.84 (12F, m, CF₃), -114.11 (8F, t, ⁴*J*_{FF} 13.3, α -CF₂), -121.51 (8F, m, CF₂), -122.59 (16F, m, 2 x CF₂), -125.88 (8F, m, CF₂); δ_{P} (121.80 MHz) 42.36 (s); δ_{C} (100.61 MHz) 10.81 (d, *J*_{CP} 51.8, CH₂), 23.45 (t, ²*J*_{CF} 22.5, CH₂); *m/z* (ES⁺) 1419 ([P(CH₂CH₂C₆F₁₃)₄]⁺, 100%); *m/z* (ES⁻) 149 (CF₃SO₃⁻, 100%).

Preparation of *n*-butyltris(1*H*,1*H*,2*H*,2*H*-perfluorooctyl)phosphonium trifluoromethane sulfonate.



A small Schlenk flask was flamed dried, back filled with nitrogen and charged with tris(1*H*,1*H*,2*H*,2*H*-perfluorooctyl)phosphine (0.50 g, 0.47 mmol), butyl trifluoromethane sulfonate (0.60 g, 2.91 mmol) and benzotrifluoride (5 cm³) and then freeze/pumped/thawed degassed to remove any dissolved gases. The reaction mixture was then heated to 45 °C under static vacuum for 48 h. After cooling the reaction mixture to room temperature, it was back filled with nitrogen and the solvent was removed by rotary evaporation to give a viscous oil. The viscous oil was triturated with hexane (10 cm³) and then toluene (10 cm³). This procedure was repeated three times before placing the salt under oil pump vacuum for a day to yield a viscous oil (Found: C, 27.4; H, 1.5, C₂₉H₂₁F₄₂O₃PS requires: C, 27.2; H, 1.6 %); δ_{H} (d₆-acetone, 300.14 MHz) 0.98 (3H, t, ³*J*_{HH} 7.7, CH₃), 1.58 (2H, m, CH₃CH₂), 1.86 (2H, m, C₂H₅CH₂CH₂P), 2.84-2.99 (8H, m, PCH₂CH₂Rf, C₃H₇CH₂PCH₂), 3.20 (6H, m, PCH₂CH₂Rf); ¹H{³¹P}NMR (300.14 MHz) 0.84 (3H, t, ³*J*_{HH} 7.2, CH₃), 1.45 (2H, m, CH₃CH₂), 1.76 (2H, m, C₂H₅CH₂CH₂P), 2.84 (2H, m, H₇C₃CH₂P), 2.97 (6H, m, PCH₂CH₂Rf), 3.09 (6H, m, PCH₂CH₂Rf); δ_{F} (376.46 MHz) -77.92 (3F, s, CF₃SO₃), -80.81 (9F, m, CF₃), -114.23 (6F, t, ⁴*J*_{FF} 14.4, α -CF₂), -121.50 (6F, m, CF₂), -122.53 (12F, m, 2 x CF₂), -125.86 (6F, m, CF₂); δ_{P} (161.97 MHz) 40.04 (s); δ_{C} (100.61 MHz) 10.64 (d, *J*_{CP} 51.8, CH₂), 12.54 (CH₃), 17.55 (d, *J*_{CP} 46.2, CH₂), 22.86 (d, *J*_{CP} 4.7, CH₂), 23.35 (2 m, 2 x CH₂); *m/z* (ES⁺) 1129 ([C₄H₉-P(CH₂CH₂C₆F₁₃)₃]⁺, 100 %); *m/z* (ES⁻) 149 (CF₃SO₃⁻, 100%).

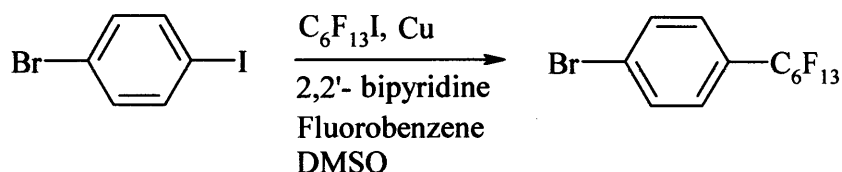
Preparation of benzyltris(1*H*,1*H*,2*H*,2*H*-perfluorooctyl)phosphonium bromide.



A small Schlenk flask was flame dried, back filled with nitrogen and charged with tris(1*H*,1*H*,2*H*,2*H*-perfluorooctyl)phosphine (1.01 g, 0.94 mmol), benzylbromide (0.96 g, 5.65 mmol) and benzotrifluoride (10 cm³), and then freeze/pumped/thawed/de-gassed. The reaction was then heated to 110 °C under static vacuum for 24 h. After cooling the reaction mixture, it was back filled with nitrogen and the solvent was removed by rotary evaporation to give a viscous oil. The viscous oil was triturated with hexane (15 cm³) and then toluene (15 cm³). This procedure was repeated three times before placing under oil pump vacuum

for a day. Finally, the salt was washed with diethyl ether (10 cm³) and dried under vacuum to yield a white powder (0.82 g, 71 %). mp 74 – 80 °C; (Found: C, 29.5; H, 1.45; P, 2.1; Br, 6.2, C₃₁H₁₉BrF₂₉P requires: C, 29.9; H, 1.5; P, 2.5; Br, 6.4 %). δ_{H} (d₆-acetone, 300.14 MHz) 3.19 (6H, m, PCH₂CH₂Rf), 3.60 (6H, m, PCH₂CH₂Rf), 5.13 (2H, d, ²J_{HP} 15.8, PhCH₂), 7.71 (3H, m, PhH), 7.95 (2H, m, PhH); ¹H{³¹P} NMR (300.14 MHz) 3.19 (6H, m, CH₂Rf), 3.60 (6H, m, RfCH₂CH₂P), 5.13 (2H, s, PhCH₂P), 7.48 (3H, m, PhH), 7.80 (2H, m, PhH); δ_{F} (282.41 MHz) - 80.85 (9F, m, CF₃), -114.25 (6F, t, ⁴J_{FF} 13.9, α -CF₂), -121.50 (6F, m, CF₂), -122.56 (12F, m, 2 x CF₂), -125.91 (6F, m, CF₂); δ_{P} (121.80 MHz) 36.92 (s); δ_{C} (100.61 MHz) 11.14 (d, J_{CP} 51.4, CH₂), 23.73 (t, ²J_{CF} 22.4, CH₂), 25.88 (d, J_{CP} 44.1, CH₂), 128.20 (d, J_{CP} 9.5, C), 128.60 (d, J_{CP} 3.9, CH), 129.42 (d, J_{CP} 2.6, CH), 130.53 (d, J_{CP} 4.9, CH); *m/z* (ES⁺) 1164 ([C₆H₅CH₂-P(CH₂CH₂C₆F₁₃)₃]⁺, 100%); *m/z* (ES⁻) 79/81 (Br⁻, 100%).

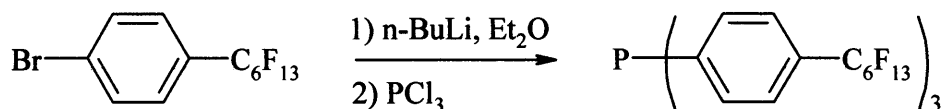
Preparation of 4-(perfluorohexyl)bromobenzene.



The preparation of 4-perfluorohexylbromobenzene was carried out following Hope's method.^{2,3} A solution of perfluoro-*n*-hexyl iodide (39.42 g, 88.39 mmol) in fluorobenzene (50 cm³) was added dropwise over 7 hours to a mixture of 4-bromoiodobenzene (25.00 g, 88.34 mmol), copper powder (12.36 g, 193.13 mmol), 2,2'-bipyridine (0.98 g, 6.36 mmol) in fluorobenzene (150 cm³) and DMSO (200 cm³) stirring at 70 °C. The mixture was then stirred at 70 °C for a further 120 hours. After cooling, the reaction mixture was poured into a beaker containing diethyl ether (200 cm³) and water (300 cm³). The mixture was filtered and the organic layer separated, washed with water (3 x 150 cm³), dried with MgSO₄ and the solvent was removed on the rotary evaporator to leave a brown oil. The oil was heated in a Kugelröhr oven at 65 °C (0.01 mmHg) to remove residual 4-bromoiodobenzene and, subsequently, the temperature of the oven was increased to 100 °C to distill the 4-(perfluorohexyl)bromobenzene and 1,4-bis(perfluorohexyl)benzene as a clear oil. The clear oil was then distilled by microfine distillation (bp 89 – 92 °C at 10 mbar) to give 4-

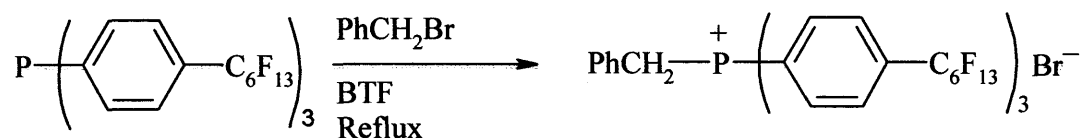
(perfluorohexyl)bromobenzene as a clear oil (28.56 g, 68 %). δ_{H} (300.14 MHz) 7.35 (2H, d, $^3J_{\text{HH}}$ 8.5, ArH), 7.55 (2H, d, $^3J_{\text{HH}}$ 8.5, ArH); δ_{F} (282.41 MHz) -81.57 (3F, t, $^4J_{\text{FF}}$ 9.9, CF₃), -111.54 (2F, t, $^4J_{\text{FF}}$ 14.6, α -CF₂), -122.02 (2F, m, CF₂), -122.49 (2F, m, CF₂), -123.42 (2F, m, CF₂), -126.78 (2F, m, CF₂); δ_{C} (75.47 MHz) 126.91 (C), 127.9 (t, $^2J_{\text{CF}}$ 24.9, C), 128.26 (t, $^3J_{\text{CF}}$ 6.0, CH), 131.95 (CH); m/z (EI) 474/476 (M⁺, 25%), 207/209 (40), 126 (20).

Preparation of tris(4-perfluorohexylphenyl)phosphine.



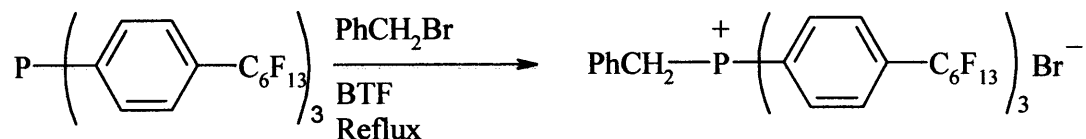
The preparation of tris(4-perfluorohexylphenyl)phosphine was carried out following Hope's method.^{2, 3} *n*-Butyllithium (10.0 cm³, 1.6 M solution in hexane, 16.0 mmol) in diethyl ether (40 cm³) was added drop wise over 1 hour to 4-(perfluorohexyl)bromobenzene (8.0 g, 17.0 mmol) in diethyl ether (200 cm³) under nitrogen at -78 °C. The mixture was allowed to warm to -50 °C for five hours whilst stirring. Phosphorus trichloride (0.66 g, 4.8 mmol) in diethyl ether (30 cm³) was then added dropwise to the reaction mixture at -78 °C over a further hour before the reaction mixture was allowed to warm slowly to room temperature over 12 hours. The mixture was hydrolysed with 10 % degassed solution of ammonium chloride (100 cm³) then the organic phase was separated, dried (MgSO₄) and the solvent was removed *in vacuo*. The product was purified by Kugelröhr distillation (225 °C at 0.01 mmHg), to afford pure tris(4-perfluorohexylphenyl)phosphine (4.50 g, 65 %). mp 65 – 68 °C (Lit.³ 63-64 °C). δ_{H} (300.14 MHz) 7.35 (2H, vt, $^3J_{\text{HH}} = ^3J_{\text{HP}}$ 8.0, ArH-2,6), 7.53 (2H, d, $^3J_{\text{HH}}$ 8.0, ArH-3,5); $^1\text{H}\{^{31}\text{P}\}$ NMR (300.14 MHz) 7.35 (2H, d, $^3J_{\text{HH}}$ 8.0, ArH-2,6), 7.53 (2H, d, $^3J_{\text{HH}}$ 8.0, ArH-3,5); δ_{F} (282.41 MHz) -81.27 (9F, t, $^4J_{\text{FF}}$ 9.9, CF₃), -111.45 (6F, t, $^4J_{\text{FF}}$ 14.6, α -CF₂), -121.87 (6F, m, CF₂), -122.16 (6F, m, CF₂), -123.22 (6F, m, CF₂), -126.55 (6F, m, CF₂); δ_{P} (121.80 MHz) -6.32 (s); δ_{C} (75.47 MHz) 127.20 (d, J_{CP} 6.8, CH), 130.12 (t, $^2J_{\text{CF}}$ 24.2, C), 133.75 (d, J_{CP} 18.8, CH), 140.41 (d, J_{CP} 15.1, C); m/z (FAB) 1216 (M⁺, 80 %).

Preparation of benzyltris(4-perfluorohexylphenyl)phosphonium bromide.



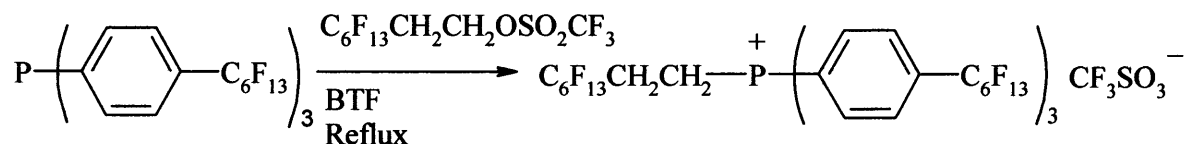
A Schlenk flask was flame dried, back filled with nitrogen and charged with tris(4-perfluorohexylphenyl)phosphine (1.00 g, 0.81 mmol), benzylbromide (0.72 g, 4.24 mmol), benzotrifluoride (5 cm³) and then freeze/pumped/thawed/degassed. The reaction mixture was heated to 100 °C under static vacuum for 32 hours. After cooling the reaction mixture to room temperature, it was back filled with nitrogen and the solvent was removed by rotary evaporation to give a viscous oil. The viscous oil was triturated with hexane (10 cm³) and then toluene (10 cm³). This procedure was repeated three times before placing under oil pump vacuum for a day. Finally, the salt was washed with diethyl ether (10 cm³) and dried under vacuum to yield a white powder (0.70 g, 70%). mp 139 – 141 °C; (Found: C, 29.5; H, 1.45; P, 2.1; Br, 6.2, C₃₁H₁₉F₃₉Br requires: C, 29.9; H, 1.5; P, 2.5; Br, 6.4 %); δ_{H} (d₆-acetone, 300.14 MHz) 6.23 (2H, d, ²J_{HP} 15.6, PhCH₂), 6.96 (2H, m, PhH), 7.20 (3H, m, PhH), 7.85 (6H, m, ArH-2,6), 8.33 (6H, m, ArH-3,5); ¹H{³¹P}NMR (300.14 MHz) 6.55 (2H, s, PhCH₂), 6.97 (2H, m, PhH), 7.0 – 7.17 (3H, m, PhH), 7.66 (6H, d, ³J_{HH} 8.3, ArH-2,6), 8.05 (6H, d, ³J_{HH} 8.3, ArH-3,5), δ_{F} (282.41 MHz) -80.77 (9F, t, ⁴J_{FF} 9.3, CF₃), -110.83 (6F, m, α -CF₂), -120.95 (12F, m, 2 x CF₂), -122.38 (6F, m, CF₂), -125.81 (6F, m, CF₂); δ_{P} (121.80 MHz) 25.34 (s); δ_{C} (101.61 MHz) 28.8 (d, J_{CP} 41.4, CH₂), 122.80 (d, J_{CP} 84.8, C), 127.34 (d, J_{CP} 8.5, C), 128.31 (dt, J_{CP} 10.1, ³J_{CF} 6.3, CH), 128.47 (m, CH), 128.65 (d, J_{CP} 2.5, CH), 131.62 (d, J_{CP} 5.3, CH), 132.65 (d, J_{CP} 10.2, CH), 134.33 (td, ²J_{CF} 24.6, J_{CP} 3.9, C); *m/z* (ES⁺) 1308/1309 ([C₆H₅CH₂P(C₆H₄C₆F₁₃)₃]⁺, 100%), *m/z* (ES⁻) 79/81 (Br⁻, 100%).

Preparation of benzyltris(4-perfluorohexylphenyl)phosphonium bromide under microwave conditions.



A small Schlenk flask was flame dried, back filled with nitrogen and charged with P(4-C₆H₄C₆F₁₃)₃ (2.00 g, 1.69 mmol), benzyl bromide (1.73 g, 1.20 cm³, 10 mmol) and benzotrifluoride (4 cm³), and then frozen/pumped/thawed/degassed. The reaction mixture was then transferred under nitrogen to a microwave tube. The sample was placed in the microwave under the following conditions: ramp time - 1 minute, 200 °C, 300 Watts, 110 Psi for 15 minutes. The reaction mixture was cooled to room temperature and opened to air before the solvent was removed using a rotary evaporator to give a viscous oil. This was immediately placed under vacuum for 1 day to give an off-white foam which was triturated with hexane (2 x 10 cm³). Removal of this final portion of hexane left an off white solid which was placed under oil pump vacuum for 2 days. Finally, the salt was washed with diethyl ether (5 cm³) to yield a white powder which was dried under vacuum (1.64 g, 71 %); *Characterisation data as above.*

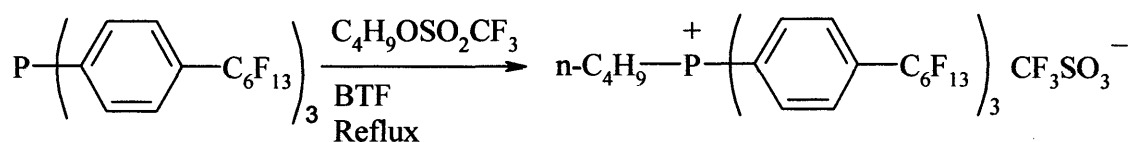
Preparation of 1H,1H,2H,2H-perfluorooctyltris (4-perfluorohexylphenyl) phosphonium trifluoromethane sulfonate.



A Schlenk flask was flame dried, back filled with nitrogen and charged with tris(4-perfluorohexylphenyl)phosphine (0.50 g, 0.41 mmol), 1H,1H,2H,2H-perfluorooctyl trifluoromethane sulfonate (0.62 g, 1.25 mmol), benzotrifluoride (10 cm³) and then frozen/pumped/thawed/degassed. The reaction mixture was heated to 84 °C under static vacuum for 96 hours. After cooling the reaction mixture to room temperature, it was back

filled with nitrogen and the solvent was removed by rotary evaporation to give a viscous oil. The viscous oil was triturated with hexane (10 cm³) and then toluene (10 cm³). This procedure was repeated three times before placing under oil pump vacuum for a day. Finally, the salt was washed with diethyl ether (10 cm³) and dried under vacuum to yield a white powder (0.35 g, 50 %). mp 157 - 162 ° C; (Found: C, 31.2; H, 0.65; P, 2.1, C₄₅H₁₆F₅₅O₃PS requires: C, 31.6; H, 0.9; P, 1.8 %); δ_{H} (d₆-acetone, 300.14 MHz) 2.87 (2H, m, CH₂Rf), 4.28 (2H, m, CH₂P), 8.06 (6H, m, ArH-3,5), 8.41 (6H, m, ArH-2,6); $^1\text{H}\{^{31}\text{P}\}$ NMR (300.14 MHz) 3.04 (2H, m, CH₂Rf) 4.43 (2H, m, CH₂P), 8.25 (6H, d, $^3J_{\text{HH}}$ 8.4, ArH-2,6), 8.53 (6H, d, $^3J_{\text{HH}}$ 8.4, ArH-3,5); δ_{F} (282.41 MHz) -78.97 (3F, s, OSO₂CF₃), -81.67 (12F, t, $^4J_{\text{FF}}$ 10.2, CF₃), -110.80 (6F, m, α -CF₂Ar), -113.37 (2F, t, $^4J_{\text{FF}}$ 12.9, α -CF₂CH₂), -120.97 (12F, m, 2 x CF₂ from Ar), -121.60 (2F, m, CF₂ from RfCH₂CH₂), -122.55 (10F, m, 1 x CF₂ from Ar, 2 x CF₂ from RfCH₂CH₂), -125.80 (8F, m, 1 x CF₂ from Ar, 1 x CF₂ from RfCH₂CH₂); δ_{P} (121.80 MHz) 27.01 (s); δ_{C} (101.61 MHz) 13.98 (d, J_{CP} 56.4, CH₂), 24.19 (t, $^2J_{\text{CF}}$ 23.1, CH₂), 122.40 (d, J_{CP} 56.4, C), 128.92 (m, CH), 135.02 (t, $^2J_{\text{CF}}$ 24.1, C), 135.44 (d, J_{CP} 11.1, CH); m/z (ES⁺) 1563 (F₁₃C₆CH₂CH₂-P(4-C₆H₄C₆F₁₃)₃⁺, 100 %); m/z (ES⁻) 149 (CF₃SO₃⁻, 100 %).

Preparation of *n*-butyltris(4-perfluorohexylphenyl)phosphonium trifluoromethane sulfonate.



A Schlenk flask was flame dried, back filled with nitrogen and charged with tris(4-perfluorohexylphenyl)phosphine (1.00 g, 0.82 mmol), butyl trifluoromethane sulfonate (0.51 g, 2.47 mmol), benzotrifluoride (10 cm³) and then frozen/pumped/thawed/degaussed. The reaction mixture was heated to 45 °C under static vacuum for 67 hours. After cooling the reaction mixture to room temperature, it was back filled with nitrogen and the solvent was removed by rotary evaporation to give a viscous oil. The viscous oil was triturated with hexane (15 cm³) and then toluene (15 cm³). This procedure was repeated three times before placing the salt under oil pump vacuum for a day. Finally, the salt was washed with diethyl ether (10 cm³) and dried under vacuum to yield a white powder (0.91 g, 78 %). mp 85 - 89 ° C; (Found: C, 34.7; H, 1.9; P, 2.6; S, 2.2, C₄₁H₂₁F₄₂O₃PS requires: C, 34.6; H, 1.5;

P, 2.2; S, 2.3 %); δ_{H} (d_6 -acetone, 300.14 MHz) 0.82 (3H, t, $^3J_{\text{HH}}$ 7.3, CH_3), 1.52 (2H, m, CH_3CH_2), 1.73 (2H, m, $\text{CH}_2\text{CH}_2\text{CH}_2$), 3.84 (2H, m, CH_2P), 8.04 (6H, m, *ArH*-3,5), 8.32 (6H, m, *ArH*-2,6); $^1\text{H}\{^{31}\text{P}\}$ NMR (300.14 MHz) 0.96 (3H, t, $^3J_{\text{HH}}$ 7.3, CH_3), 1.66 (2H, sextet, $^3J_{\text{HH}}$ 7.3, CH_3CH_2), 1.86 (2H, m, $\text{CH}_3\text{CH}_2\text{CH}_2$), 3.95 (2H, m, CH_2P), 8.18 (6H, d, $^3J_{\text{HH}}$ 8.0, *ArH*-3,5), 8.43 (6H, d, $^3J_{\text{HH}}$ 8.0, *ArH*-2,6); δ_{F} (121.80 MHz) -78.92 (3F, s, OSO_2CF_3), -81.62 (9F, m, CF_3), -111.72 (6F, t, $^4J_{\text{FF}}$ 13.3, $\alpha\text{-CF}_2$), -121.52 (12F, m, 2 x CF_2), -123.28 (6F, m, CF_2), -126.72 (6F, m, CF_2); δ_{P} (121.80 MHz) 25.99 (s); δ_{C} (100.61 MHz) 12.56 (CH_3), 20.58 (d, J_{CP} 48.0, CH_2), 23.19 (d, J_{CP} 17.5, CH_2), 23.99 (d, J_{CP} 4.5, CH_2), 122.85 (d, J_{CP} 85.0, C), 128.82 (dt, J_{CP} 12.6, $^3J_{\text{CF}}$ 6.3, CH), 134.62 (t, $^2J_{\text{CF}}$ 23.3, C), 135.18 (d, J_{CP} 10.9, CH); m/z (ES^+) 1273/1274 ($\text{C}_4\text{H}_9\text{-P(4-C}_6\text{H}_4\text{C}_6\text{F}_{13})_3^+$, 100 %); m/z (ES^-) 149 (CF_3SO_3^- , 100 %).

General Procedure for Partition Coefficients.

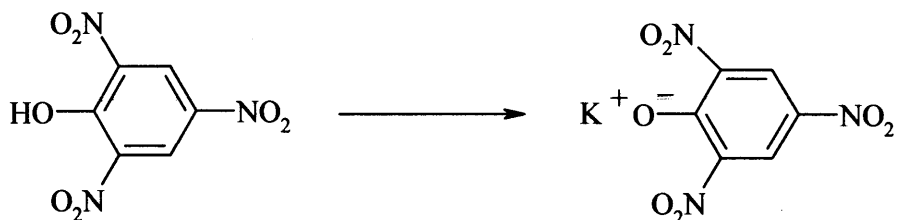
The salt was first weighed out (50 – 100 mg) and placed in a sample vial. The organic solvent (4 cm^3) and the perfluorocarbon solvent (PP3 or PFOB) (4 cm^3) were measured out and placed in a separate sample vial containing a magnetic stirrer bar and the salt added. The samples were stirred at room temperature for 30 minutes, then left to stand for 30 minutes in order for the phases to separate. A sample was removed from each phase (2 cm^3) and the solvent removed, dried under vacuum (0.01 mmHg) and then weighed.

General Procedure for Separation on FRP Silica Gel.

The fluororous – tagged phosphonium salt (80 mg) was dissolved in acetone (5 cm^3) and FRPSG (100 - 200 mg) was added. The solvent was removed by rotary evaporation and the sample was loaded onto a short column of FRPSG (0.95 g). A fluorophobic solvent (25 cm^3) was passed down the column and monitored by TLC. A fluorophilic solvent (25 cm^3) was then passed down the column and monitored by TLC. The solvents were removed and the resulting fractions were dried under vacuum (0.01 mmHg at room temperature) for 30 minutes. The weights of each fraction were noted.

5.3 Experimental Details for Chapter Three.

Preparation of potassium picrate.



The preparation of potassium picrate was carried out following Coplans's method.⁴ Potassium carbonate was added to a saturated solution of picric acid (40 cm³) at 80 °C until no more CO₂ was evolved. The solution was cooled slowly to 0 °C at which point potassium picrate crystallises out of solution. The crystals are crushed cautiously (impact and friction sensitive) before filtering and washing with cold water (30 cm³) to yield potassium picrate. δ_H (d₆-acetone, 300.14 MHz) 8.50 ppm (2H, s, ArH-3,5).

General procedure for picrate extractions.

The potassium picrate extraction procedures were adapted from Hausner's protocol.⁵ The fluorine-tagged phosphonium salt (0.01 mmol) was dissolved in BTF (100 cm³). From this 0.1mM solution, 10 cm³ of sample was removed and placed in a round bottom flask. A 0.1mM solution of aqueous potassium picrate (0.014 g in 500 cm³) was prepared and 10 cm³ removed and placed in the round bottom flask containing the dissolved fluorine salt. The phases were stirred at room temperature for 30 minutes and left to settle for 30 minutes. A sample from the aqueous phase was removed and UV analysis obtained. In order to carry out the 2:1 ratio of potassium picrate to fluorine-tagged phosphonium salt, the above procedure was used except halve the amount of catalyst (5 cm³ of 0.1 mM stock solution) was used in each case.

General procedure for the halide exchange of benzyl chloride to benzyl bromide under solid-liquid conditions.

Benzyl chloride (0.630 g, 5 mmol), lithium bromide (0.438 g, 5 mmol), biphenyl (0.200 g, 1.3 mmol) and a phase transfer catalyst (0.25 mmol) were added to benzonitrile (2

cm³). The reaction mixture was refluxed for 6 hours and monitored by gc every hour to determine the conversion to product using biphenyl as the internal standard. (Initial temperature: 120 °C for 2 minutes, 40 °C/min ramp to 150 °C for 2.25 minutes. Injector temperature: 300 °C, detector temperature: 300 °C. R_t 1.56 (benzyl chloride), R_t 1.80 (benzyl bromide), R_t 3.23 (biphenyl)).

General procedure for the halide exchange of octyl chloride to octyl bromide under solid-liquid conditions.

Octyl chloride (0.745 g, 5 mmol), lithium bromide (0.438 g, 5 mmol), biphenyl (0.200 g, 1.3 mmol) and a phase transfer catalyst (0.25 mmol) were added to benzotrifluoride (2 cm³). The reaction mixture was refluxed for 22 hours and monitored by gc to determine the conversion to product using biphenyl as the internal standard.. (Initial temperature: 120 °C for 2 minutes, 40 °C/min ramp to 150 °C for 2.25 minutes. Injector temperature: 300 °C, detector temperature: 300 °C. R_t 1.64 (octyl chloride), R_t 1.95 (octyl bromide), R_t 3.23 (biphenyl)).

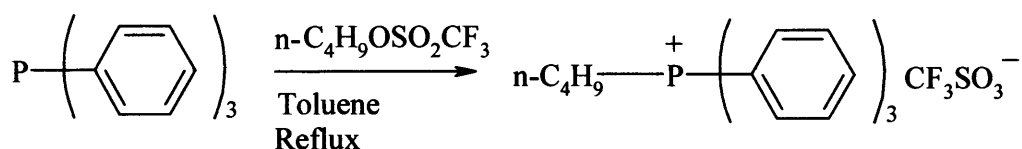
General procedure for the halide exchange of octyl bromide to octyl iodide under liquid-liquid conditions.

Octyl bromide (0.200 g, 1.0 mmol), biphenyl (0.100 g, 0.65 mmol) and a phase transfer catalyst (0.02 mmol) were added to benzotrifluoride (4 cm³). Potassium iodide (0.880 g, 5.3 mmol) was dissolved in water (2 cm³) and added to the reaction mixture. The mixture was refluxed for 16 hours and monitored by gc at 2 hourly intervals to determine the conversion to product using biphenyl as the internal standard. (Initial temperature: 120 °C for 2 minutes, 40 °C/min ramp to 150 °C for 2.25 minutes. Injector temperature: 300 °C, detector temperature: 300 °C. R_t 1.94 (octyl bromide), R_t 2.41 (octyl iodide), R_t 3.23 (biphenyl)).

General procedure for the halide exchange of octyl bromide to octyl iodide under solid-liquid conditions.

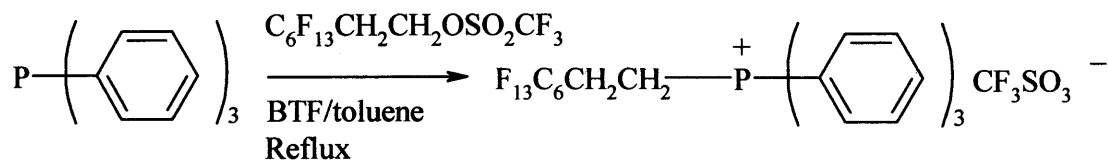
Octyl bromide (0.200 g, 1.0 mmol), potassium iodide (0.880 g, 5.3 mmol), biphenyl (0.100 g, 0.65 mmol) and a phase transfer catalyst (0.02 mmol) were added to benzotrifluoride (4 cm³) and refluxed for 24 hours. The reaction was monitored by gc to determine the conversion to product using biphenyl as the internal standard.

Preparation of butyltriphenylphosphonium trifluoromethane sulfonate.



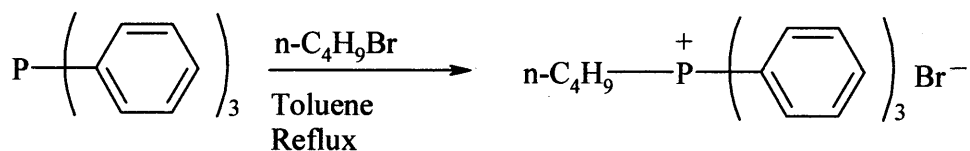
A Schlenk flask was flame dried, back filled with nitrogen and charged with triphenylphosphine (1.00 g, 3.8 mmol), butyl trifluoromethane sulfonate (2.36 g, 11.5 mmol), toluene (5 cm³) and then frozen/pumped/thawed/degassed three times. The reaction mixture was heated to 45 °C under static vacuum for 1 hour. After cooling the reaction mixture to room temperature, it was back filled with nitrogen and filtered to leave a white solid which was washed with toluene (10 cm³) and dried under oil pump vacuum (0.01 mmHg) to afford butyltriphenylphosphonium trifluoromethane sulfonate as a white powder (0.88 g, 50 %). mp 99 - 100 °C; (Found: C, 58.89; H, 5.03, C₂₃H₂₄F₃PSO₃ requires C, 58.97; H, 5.13 %); δ_{H} (CDCl₃, 300.14 MHz) 0.90 (3H, t, ³J_{HH} 7.0, CH₃), 1.59 (4H, m, 2 x CH₂), 3.28 (2H, m, CH₂P), 7.70 (12H, m, ArH), 7.80 (3H, m, ArH-4); ¹H{³¹P} NMR (300.14 MHz) 0.91 (3H, t, ³J_{HH} 7.1, CH₃), 1.59 (4H, m, 2 x CH₂), 3.29 (2H, m, CH₂P), 7.71 (12H, d, ³J_{HH} 6.0, ArH), 7.80 (3H, m, ArH-4); δ_{F} (282.41 MHz) -78.19 (3F, s, CF₃SO₃); δ_{P} (121.80 MHz) 23.92 (s); δ_{C} (100.61 MHz) 13.50 (CH₃), 21.92 (d, J_{CP} 50.5, CH₂), 23.60 (d, J_{CP} 16.7, CH₂), 24.39 (d, J_{CP} 4.4, CH₂), 118.12 (d, J_{CP} 86.1, C), 130.59 (d, J_{CP} 12.5, CH), 133.37 (d, J_{CP} 9.3, CH), 135.21 (d, J_{CP} 2.2, C); *m/z* (ES⁺) 319 ([C₄H₉-PPh₃]⁺, 100%); *m/z* (ES⁻) 149 (CF₃SO₃⁻, 100%).

Preparation of 1*H*,1*H*,2*H*,2*H*-perfluorooctyltriphenylphosphonium trifluoromethane sulfonate.



A Schlenk flask was flame dried, back filled with nitrogen and charged with triphenylphosphine (1.0 g, 3.8 mmol), 1*H*,1*H*,2*H*,2*H*-perfluorooctyltrifluoromethanesulfonate (5.12 g, 11.4 mmol), benzotrifluoride/toluene (1:1, 8 cm³) and then freeze/pumped/thawed/degassed three times. The reaction mixture was heated to 80 °C under static vacuum for 1 hour. After cooling the reaction mixture to room temperature, it was back filled with nitrogen and decanted to leave an off white viscous oil which was washed with hexane (10 cm³) before drying under vacuum (0.01 mmHg), to yield a white powder (1.24 g, 43 %). mp 81 - 83 °C; (Found: C, 42.65; H, 2.60, C₂₇H₁₉F₁₆PSO₃ requires: C, 42.74; H, 2.51 %); δ_H (d₆-acetone, 300.14 MHz) 2.42 (2H, m, CH₂Rf), 3.62 (2H, m, CH₂P), 7.67 (12H, m, ArH), 7.76 (3H, m, ArH-4); δ_F (282.41 MHz) -78.00 (3F, s, OSO₂CF₃), -80.47 (3F, t, ⁴J_{FF} 10.0, CF₃) -113.98 (2F, t, ⁴J_{FF} 15.0, α-CF₂), -121.94 (2F, m, CF₂), -122.93 (4F, m, 2 x CF₂), -126.20 (2F, m, CF₂); δ_P (121.80 MHz) 25.13 (s); δ_C (100.61 MHz) 14.81 (d, J_{CP} 57.6, CH₂), 24.45 (t, ²J_{CF} 21.0, CH₂), 116.61 (d, J_{CP} 88.0, C), 130.90 (d, J_{CP} 12.7, CH), 133.51 (d, J_{CP} 10.1, CH), 135.76 (C); *m/z* (ES⁺) 609 ([C₆F₁₃C₂H₄-PPh₃]⁺, 100%); (ES⁻) 149 (CF₃SO₃⁻, 100%).

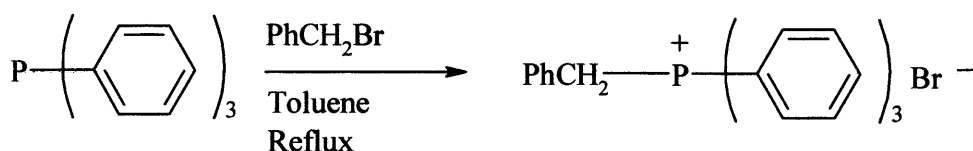
Preparation of *n*-butyltriphenylphosphonium bromide.



A solution of triphenylphosphine (5.84 g, 22 mmol), butyl bromide (16.59 g, 121 mmol) and dry toluene (80 cm³) was refluxed under nitrogen for 24 hours. On cooling to room temperature the white precipitate was filtered off, washed with toluene and diethyl ether

and finally dried to yield a white solid (9.63 g, 99 %). mp 236 - 240 °C (Lit.⁶ 242 - 243 °C); δ_{H} (CDCl₃, 300.14 MHz) 0.89 (3H, t, $^3J_{\text{HH}}$ 7.2, CH₃), 1.67 (4H, m, 2 x CH₂), 3.75 (2H, m, CH₂P), 7.60 – 7.85 (15H, m, ArH); δ_{P} (121.80 MHz) 24.50 (s); δ_{C} (100.61 MHz) 13.59 (CH₃), 22.47 (d, J_{CP} 85.03, CH₂), 23.56 (d, J_{CP} 15.8, CH₂), 24.40 (d, J_{CP} 3.8, CH₂), 118.01 (d, J_{CP} 50.6, C), 130.43 (d, J_{CP} 12.8, CH), 133.42 (d, J_{CP} 9.8, CH), 135.00 (CH); m/z (ES⁺) 319/320 (Bu-PPh₃⁺, 100 %); m/z (ES⁻) 79/81 (Br⁻, 100 %).

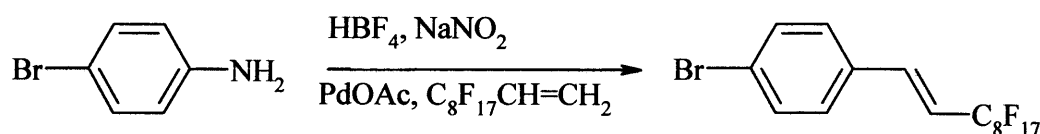
Preparation of benzyltriphenylphosphonium bromide.



A solution of triphenylphosphine (6.01 g, 23 mmol), benzylbromide (4.70 g, 3.27 cm³, 28 mmol) and dry toluene (80 cm³) was refluxed under nitrogen for 19 hours. On cooling to room temperature the white precipitate was filtered off, washed with toluene and diethyl ether and finally dried to yield a white solid (10.73 g, 95 %). mp 292 - 295 °C (Lit.⁷ 287 - 291 °C); δ_{H} (CDCl₃, 300.14 MHz) 5.23 (2H, d, $^2J_{\text{HP}}$ 14.4, CH₂P), 7.02 (5H, m, PhH), 7.68 (15H, m, ArH); $^1\text{H}\{^{31}\text{P}\}$ NMR (300.14 MHz) 5.24 (2H, s, CH₂P), 7.01 (5H, m, PhH), 7.65 (15H, m, ArH); δ_{P} (121.80 MHz) 23.15 (s); δ_{C} (100.61 MHz) 30.84 (d, J_{CP} 47.5, CH₂), 117.70 (d, J_{CP} 86.2, C), 127.09 (d, J_{CP} 8.3, C), 128.41 (d, J_{CP} 3.8, CH), 128.81 (d, J_{CP} 3.1, CH), 130.17 (d, J_{CP} 12.9, CH), 131.47 (d, J_{CP} 5.3, CH), 134.35 (d, J_{CP} 9.8, CH), 135.03 (d, J_{CP} 2.3, CH); m/z (ES) 353 (PhCH₂-PPh₃⁺, 100 %); m/z (ES⁻) 79/81 (Br⁻, 100 %).

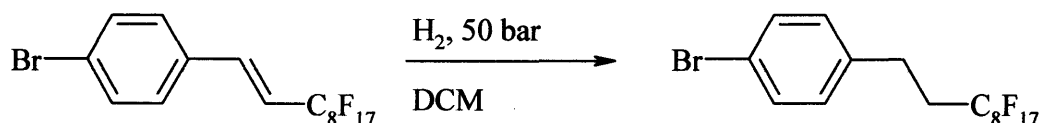
5.4 Experimental Details for Chapter Four.

Preparation of 4-(1*H*,2*H*-perfluorodec-1-ene)bromobenzene.



The preparation of 4-(1*H*,2*H*-perfluorodec-1-ene)bromobenzene was carried out following the procedure of Genet.⁸ 4-Bromoaniline (6.88 g, 44 mmol) and tetrafluoroboric acid (14 cm³) were stirred together for 30 minutes at -5 °C using an ice/salt bath. Sodium nitrite (2.76 g, 40 mmol) dissolved in water (10 cm³) was added dropwise to the reaction mixture whilst stirring and maintaining a temperature of -5 °C. The reaction mixture was left to stir for a further 30 minutes before filtering the mixture and washing with diethyl ether (100 cm³) to afford the diazonium salt as an off white solid (11.90 g, 100 %). The solid was used without further purification. The diazonium salt (11.95 g, 44 mmol) and palladium acetate (0.40 g, 1.78 mmol) were added to methanol (100 cm³) and the mixture stirred at room temperature. 1*H*,2*H*-perfluorodec-1-ene (19.62 g, 44 mmol) was added dropwise over 1 hour. The mixture was stirred for a further 1 hour until the colour changed from orange to black. The solvent was removed by rotary evaporation to leave a black solid which was dissolved in petroleum ether (40-60 °C, 250 cm³) and passed through silica to remove the palladium catalyst. The solvent was finally removed by rotary evaporation to leave the product as a white solid which was dried under vacuum (0.01 mmHg, 20 °C) (18.00 g, 70 %). mp 38 – 40 °C (Lit.⁸ 45 °C); δ_{H} (300.14 MHz) 6.09 (1H, dt, $^3J_{\text{HH}}$ 16.0, $^3J_{\text{HF}}$ 12.0, CH=CH*Rf*), 7.01 (1H, dt, $^3J_{\text{HH}}$ 16.0, $^4J_{\text{HF}}$ 4.0, CH=CH*Rf*), 7.22 (2H, d, $^3J_{\text{HH}}$ 8.0, ArH), 7.34 (2H, d, $^3J_{\text{HH}}$ 8.0, ArH). δ_{F} (282.41 MHz) -81.11 (3F, t, $^4J_{\text{FF}}$ 12.0, CF₃), -111.44 (2F, t, $^4J_{\text{FF}}$ 13.5, α -CF₂), -121.53 (2F, m, CF₂), -122.06 (4F, m, 2 x CF₂), -122.85 (2F, m, CF₂), -123.24 (2F, m, CF₂), -126.36 (2F, m, CF₂). δ_{C} (100.61 MHz) 115.09 (t, $^2J_{\text{CF}}$ 23.2, CH), 124.40 (CH), 129.03 (C), 132.20 (CH), 132.42 (C), 138.53 (t, $^3J_{\text{CF}}$ 9.5, CH); *m/z* (FAB) 600 /602 (*M*⁺, 100%).

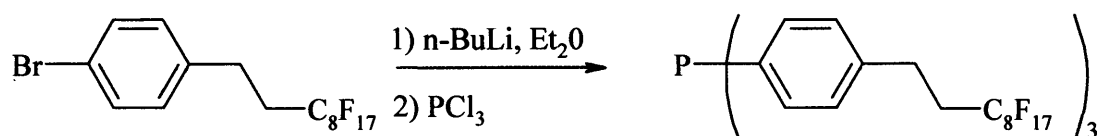
Preparation of 4-(1*H*,1*H*,2*H*,2*H*-perfluorodecyl)bromobenzene.



The preparation of 4-(1*H*,1*H*,2*H*,2*H*-perfluorodecyl)bromobenzene was carried out following the procedure of Genet.⁸ 4-(1*H*,2*H*-perfluorodec-1-ene)bromobenzene (18.86 g, 31.4 mmol) and Rh/C (0.20 g) were added to dichloromethane (30 cm³) and the reaction mixture was placed under hydrogen (50 bar) for 24 hours at 20 °C. The solvent was

removed by rotary evaporation to leave a black solid which was dissolved in petroleum ether (40 – 60 °C, 100 cm³) and then passed through silica. The solvent was removed by rotary evaporation to yield 4-(1*H*,1*H*,2*H*,2*H*-perfluorodecyl)bromobenzene as a white solid (15.57 g, 82 %). mp 52 – 54 °C (Lit.⁸ 54 °C); δ_{H} (300.14 MHz) 2.27 (2H, m, CH₂), 2.80 (2H, m, CH₂), 7.02 (2H, d, ³*J*_{HH} 8.5, ArH), 7.35 (2H, d, ³*J*_{HH} 8.5, ArH); δ_{F} (282.41 MHz) - 81.25 (3F, t, ⁴*J*_{FF} 10.2, CF₃), -115.05 (2F, t, ⁴*J*_{FF} 12.2, α -CF₂), -122.40 (6F, m, 3 x CF₂), -123.21 (2F, m, CF₂), -123.95 (2F, m, CF₂), -126.61 (2F, m, CF₂); δ_{C} (75.47 MHz) 25.91 (CH₂), 32.73 (t, ²*J*_{CF} 21.9, CH₂), 118.60 (CH), 129.96 (C), 132.28 (CH), 138.05 (C); *m/z* (FAB) 602/604 (MH⁺, 100%).

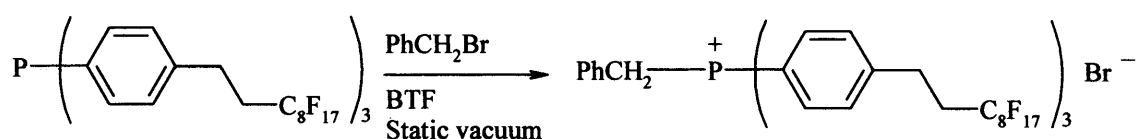
Preparation of tris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl)phosphine.



The preparation of tris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl)phosphine was adapted from Genet's method.⁸ *n*-Butyllithium (7.3 cm³, 1.6 M solution in hexane, 11.7 mmol) in diethyl ether (30 cm³) was added drop wise over 1 hour to 4-(1*H*,1*H*,2*H*,2*H*-perfluorodecyl)bromobenzene (6.90 g, 11.4 mmol) in diethyl ether (400 cm³) at -30 °C under nitrogen. The mixture was allowed to warm to -15 °C for two hours whilst stirring. Phosphorus trichloride (0.28 g, 3.3 mmol) in diethyl ether (30 cm³) was then added dropwise to the reaction mixture at -30 °C over a further hour before the reaction mixture was allowed to warm slowly to room temperature overnight. The mixture was hydrolysed with a degassed 10 % solution of ammonium chloride (100 cm³), then the organic phase was separated, dried (MgSO₄) and the solvent was removed *in vacuo*. The product was purified by Kugelröhr distillation to remove 4-(1*H*,1*H*,2*H*,2*H*-perfluorodecyl)bromobenzene (160 °C at 0.01 mmHg) and to afford tris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl)phosphine (3.32 g, 54 %). mp 95 – 98 °C, (Lit.⁸ 88 °C); δ_{H} (300.14 MHz) 2.32 (6H, m, CH₂), 2.83 (6H, m, CH₂), 7.10 – 7.34 (12H, m, ArH); ¹H{³¹P}NMR (121.80 MHz) 2.34 (6H, m, CH₂), 2.84 (6H, m, CH₂), 7.09 (6H, d, ³*J*_{HH} 8.0, ArH-3,5), 7.16 (6H, d, ³*J*_{HH} 8.0, ArH-2,6); δ_{F} (282.41 MHz) -80.83 (9F, t, ⁴*J*_{FF} 9.0, CF₃), -111.58 (6F, t,

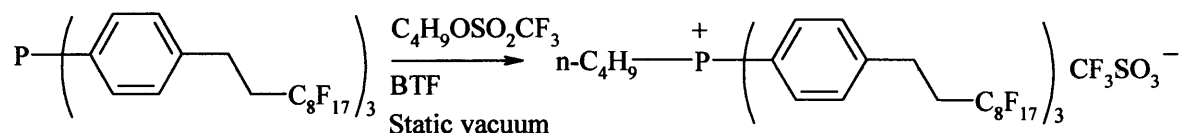
$^4J_{\text{FF}}$ 11.0, $\alpha\text{-CF}_2$), -121.87 (18F, m, 3 x CF_2), -122.16 (6F, m, CF_2), -123.22 (6F, m, CF_2), -126.55 (6F, m, CF_2); δ_{P} (121.80 MHz) -7.41 (s), δ_{C} (75.47 MHz) 25.22 (CH_2), 31.72 (t, $^2J_{\text{CF}}$ 22.01, CH_2), 127.53 (d, J_{CP} 6.8, CH), 133.09 (d, J_{CP} 19.6, CH), 134.47 (d, J_{CP} 10.6, C) 138.90 (C); m/z (FAB) 1600 (M^+ , 100 %).

Preparation of benzyltris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl)phosphonium bromide.



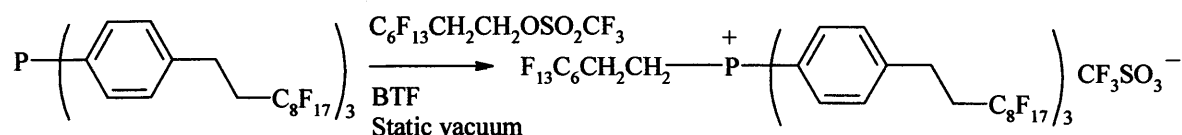
A Schlenk flask was flame dried, back filled with nitrogen and charged with tris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl)phosphine (0.50 g, 0.31 mmol), benzylbromide (0.40 g, 2.35 mmol), benzotrifluoride (5 cm^3) and then freeze/pumped/thawed/degassed three times. The reaction mixture was heated to 110 °C under static vacuum for 30 minutes. After cooling the reaction mixture to room temperature, it was back filled with nitrogen and the solvent was removed by rotary evaporation to give a viscous oil. The viscous oil was triturated with hexane (3 x 10 cm^3) and the salt placed under oil pump vacuum (0.01 mmHg) for a day. Finally, the salt was washed with a hexane/diethyl ether mix (1:1) and dried under vacuum to afford a white powder (0.29 g, 53 %). mp 138 – 145 °C; (Found: C, 37.39; H, 1.81, $\text{C}_{55}\text{H}_{31}\text{F}_{51}\text{BrP}$ requires C, 37.29; H, 1.75 %); δ_{H} (d_6 -acetone, 300.14 MHz) 2.97 (6H, m, CH_2), 3.03 (6H, m, CH_2), 5.62 (2H, d, $^2J_{\text{HP}}$ 15.3, CH_2P), 7.03 - 7.20 (5H, m, PhH), 7.55 (6H, d, $^3J_{\text{HH}}$ 8.0, ArH-3,5), 7.81 (6H, dd, $^3J_{\text{HP}}$ 11.7, $^3J_{\text{HH}}$ 8.0, ArH-2,6); $^1\text{H}\{^{31}\text{P}\}$ NMR (300.14 MHz) 2.97 (6H, m, CH_2), 3.00 (6H, m, CH_2), 5.62 (2H, s, CH_2P), 7.03-7.12 (5H, m, PhH), 7.56 (6H, d, $^3J_{\text{HH}}$ 8.0, ArH-3,5), 7.81 (6H, d, $^3J_{\text{HH}}$ 8.0, ArH-2,6); δ_{F} (282.41 MHz) -81.66 (9F, t, $^4J_{\text{FF}}$ 10.0, CF_3), -114.83 (6F, $^4J_{\text{FF}}$ 12.0, $\alpha\text{-CF}_2$), -122.40 (18F, m, 3 x CF_2), -123.23 (6F, m, CF_2), -124.43 (6F, m, CF_2), -126.99 (6F, m, CF_2); δ_{P} (121.80 MHz) 23.54 (s); δ_{C} (101.61 MHz) 26.13 (CH_2), 31.35 (t, $^2J_{\text{CF}}$ 21.6, CH_2), 116.69 (d, J_{CP} 87.5, C), 128.03 (d, J_{CP} 3.2, CH), 128.55 (m, C), 128.64 (d, J_{CP} 3.2, CH), 130.13 (d, J_{CP} 13.0, CH), 131.58 (d, J_{CP} 5.0, CH), 134.85 (d, J_{CP} 10.0, CH), 147.18 (d, J_{CP} 2.0, C); m/z (ES^+) 1692 ($[\text{C}_6\text{H}_5\text{CH}_2\text{P}(\text{C}_6\text{H}_4\text{CH}_2\text{CH}_2\text{C}_8\text{F}_{17})_3]^+$ 100%); m/z (ES^-) 79/81 (Br^- , 100%).

Preparation of butyltris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl)phosphonium trifluoromethanesulfonate.



A Schlenk flask was flame dried, back filled with nitrogen and charged with tris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl)phosphine (0.50 g, 0.3 mmol), *n*-butyl trifluoromethane-sulfonate (0.32 g, 1.6 mmol), benzotrifluoride (5 cm³) and then frozen/pumped/thawed/degassed three times. The reaction mixture was heated to 45 °C under static vacuum for 3 hours. After cooling the reaction mixture to room temperature, it was back filled with nitrogen and the solvent was removed by rotary evaporation to give a viscous oil. The viscous oil was triturated with hexane (3 x 10 cm³) before placing the salt under oil pump vacuum (0.01 mmHg) for a day. Finally, the salt was washed with a hexane/diethyl ether mix (1:1, 10 cm³) and dried under vacuum to leave a viscous brown oil (0.25 g, 45 %). (Found: C, 35.31; H, 1.83, C₅₃H₃₃F₅₄PSO₃ requires C, 35.22; H, 1.84 %); δ_{H} (d₆-acetone, 300.14 MHz) 0.84 (3H, t, ³*J*_{HH} 7.5 CH₃), 1.52 (2H, m, CH₂CH₃), 1.63 (2H, m, CH₂CH₂CH₃), 2.86 (6H, m, CH₂Ar), 3.05 (6H, m, CH₂Rf), 3.45 (2H, m, CH₂P), 7.75 (6H, dd, ³*J*_{HP} 11.0, ³*J*_{HH} 8.2, Ar*H*-2,6), 7.80 (6H, d, ³*J*_{HH} 8.2, Ar*H*-3,5); ¹H{³¹P} NMR (300.14 MHz) 0.84 (3H, t, ³*J*_{HH} 7.5, CH₃), 1.52 (2H, m, CH₂CH₃), 1.62 (2H, m, CH₂CH₂CH₃), 2.58 (6H, m, CH₂Ar), 3.08 (6H, m, CH₂Rf), 3.48 (2H, m, CH₂), 7.74 (6H, d, ³*J*_{HH} 8.2, Ar*H*-2,6), 7.84 (6H, d, ³*J*_{HH} 8.2, Ar*H*-3,5); δ_{F} (282.41 MHz) -78.99 (3F, s, CF₃SO₃), -81.65 (9F, t, ⁴*J*_{FF} 10.0, CF₃), -114.63 (6F, t, ⁴*J*_{FF} 12.0, α-CF₂), -122.39 (18F, m, 3 x CF₂), -123.23 (6F, m, CF₂), -123.89 (6F, m, CF₂) -126.72 (6F, m, CF₂); δ_{P} 23.36 (s); δ_{C} (100.61 MHz), 12.67 (CH₃), 20.81 (d, *J*_{CP} 51.3, CH₂), 23.40 (d, *J*_{CP} 16.1, CH₂), 24.20 (d, *J*_{CP} 3.0, CH₂), 26.14 (CH₂), 31.34 (t, ²*J*_{CF} 21.6, CH₂), 116.92 (d, *J*_{CP} 87.5, C), 130.60 (d, *J*_{CP} 11.8, CH), 133.99 (d, *J*_{CP} 11.1, CH), 147.46 (C); *m/z* (ES⁺) 1658 ([C₄H₉-P(C₆H₄CH₂CH₂C₈F₁₇)₃]⁺, 100%); *m/z* (ES⁻) 149 (CF₃SO₃⁻, 100%).

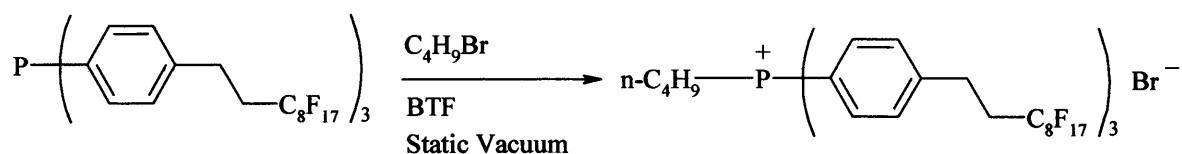
Preparation of 1*H*,1*H*,2*H*,2*H*-perfluorooctyltris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl) phosphonium trifluoromethanesulfonate.



A Schlenk flask was flame dried, back filled with nitrogen and charged with tris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl)phosphine (0.50 g, 0.3 mmol), 1*H*,1*H*,2*H*,2*H*-perfluorooctyl trifluoromethanesulfonate (0.78 g, 11.4 mmol), benzotrifluoride (5 cm³) and then frozen/pumped/thawed/degassed three times. The reaction mixture was heated to 80 °C under static vacuum for 1 hour. After cooling the reaction mixture to room temperature, it was back filled with nitrogen and the solvent was removed by rotary evaporation to give a viscous oil. The viscous oil was triturated with hexane (10 cm³). The salt was then distilled to remove excess 1*H*,1*H*,2*H*,2*H*-perfluorooctyl trifluoromethanesulfonate (0.1 mmHg, 65 °C). Benzotrifluoride (30 cm³) was added to the viscous oil and the organic layer was washed with water (3 x 30 cm³). The organic layer was separated, dried (MgSO₄) and the solvent was removed by rotary evaporation. The remaining viscous brown oil was dried under oil pump vacuum (0.01 mmHg) for 1 day. Toluene/diethyl ether (1:1, 10 cm³) was added to the oil and stirred for 1 day, the solvent removed and dried under vacuum to leave a yellowy brown oily solid (0.81 g, 83 %). (Found: C, 32.57; H, 1.30, C₅₇H₂₈F₆₇PSO₃ requires: C, 32.63, H, 1.34 %); δ_{H} (d₆-acetone, 300.14 MHz) 2.55 (6H, m, CH₂), 2.63 (2H, m, CH₂Rf), 3.06 (6H, m, CH₂), 3.90 (2H, m, CH₂P), 7.74 (6H, m, ArH-3,5), 7.87 (6H, dd, ³J_{HP} 9.0, ³J_{HH} 8.0, ArH-2,6); ¹H{³¹P} NMR (300.13 MHz) 2.55 (6H, m, CH₂), 2.64 (2H, m, CH₂Rf), 3.06 (6H, m, CH₂), 3.89 (2H, m, CH₂P), 7.74 (6H, d, ³J_{HH} 8.0, ArH-3,5), 7.87 (6H, d, ³J_{HH} 8.0, ArH-2,6); δ_{F} (282.41 MHz) -78.87 (3F, s, OSO₂CF₃), -81.66 (12F, bt, ⁴J_{FF} 11.5, CF₃), -114.45 (2F, t, ⁴J_{FF} 17.2, α -CF₂-alkyl), -114.61 (6F, t, ⁴J_{FF} 15.2, α -CF₂Ar), -122.43 (20F, m, CF₂'s), -123.24 (6F, m, CF₂), -123.43 (4F, m, CF₂) -123.92 (6F, m, CF₂), -126.75 (8F, m, CF₂); δ_{P} (121.80 MHz) 24.42 (s); δ_{C} (100.61 MHz) 14.33 (d, J_{CP} 57.4, CH₂), 24.49 (t, ²J_{CF} 23.1, CH₂), 26.18 (CH₂), 31.33 (t, ²J_{CF}, 22.1, CH₂), 115.60 (d, J_{CP} 88.6, C), 130.79 (d, J_{CP} 13.1, CH), 134.22 (d, J_{CP} 10.1, CH), 148.01

(d, J_{CP} 3.0, C); m/z (ES^+) 1948 ($[C_6F_{13}CH_2CH_2-P(C_6H_4CH_2CH_2C_8F_{17})_3]^+$ 100%); m/z (ES^-) 149 ($CF_3SO_3^-$, 100%).

Preparation of butyltris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl)phosphonium bromide.



A Schlenk flask was flame dried, back filled with nitrogen and charged with tris(4-1*H*,1*H*,2*H*,2*H*-perfluorodecylphenyl) phosphine (0.50 g, 0.3 mmol), freshly distilled butyl bromide (0.64 g, 4.7 mmol), benzotrifluoride (5 cm³) and then freeze/pumped/thawed/degassed three times. The reaction mixture was heated to 110 °C under static vacuum for 72 hours. After cooling the reaction mixture to room temperature, it was back filled with nitrogen and the solvent was removed by rotary evaporation to give a brown viscous oil. The viscous oil was triturated with hexane (10 cm³) for one day to yield a white powder. Finally, the salt was washed with diethyl ether (10 cm³) then placed under oil pump vacuum (0.01 mmHg) to yield a white powder (0.35 g, 64 %). mp 98 – 102 °C; (Found: C, 35.31; H, 1.83, C₅₃H₃₃F₅₄PSO₃ requires C, 35.22; H, 1.74 %); δ_H (d₆-acetone, 300.14 MHz) 0.79 (3H, t, $^3J_{HH}$ 7.0, CH₃); 1.52 (2H, m, CH₂CH₃), 2.55 (8H, m, CH₂), 3.03 (6H, m, CH₂), 3.70 (2H, m, CH₂P), 7.68 (6H, m, ArH-3,5), 7.85 (6H, dd, $^3J_{HP}$ 12.7, $^3J_{HH}$ 8.3, ArH-2,6), $^1H\{^{31}P\}$ NMR (300.14 MHz) 0.80 (3H, t, $^3J_{HH}$ 7.0, CH₃); 1.54 (2H, m, CH₂CH₃), 2.57 (8H, m, CH₂), 3.05 (6H, m, CH₂), 3.72 (2H, m, CH₂P), 7.69 (6H, d, $^3J_{HH}$ 8.0, ArH-3,5), 7.84 (6H, d, $^3J_{HH}$ 8.0, ArH-2,6); δ_F (282.41 MHz) -81.63 (9F, t, $^4J_{FF}$ 10.0, CF₃), -114.64 (6F, t, $^4J_{FF}$ 13.0, α -CF₂), -121.18 (6F, m, CF₂), -122.40 (12F, m, 2 x CF₂), -123.86 (6F, m, CF₂), -124.43 (6F, m, CF₂), -127.78 (6F, m, CF₂); δ_P (121.80 MHz) 23.62 (s); δ_C (100.61 MHz) 12.84 (CH₃), 21.44 (d, J_{CP} 51.3, CH₂), 23.85 (d, J_{CP} 17.1, CH₂), 24.29 (d, J_{CP} 4.0, CH₂), 26.13 (CH₂), 31.36 (t, $^2J_{CF}$ 21.5, CH₂), 116.34 (d, J_{CP} 87.0, C), 130.50 (d, J_{CP} 13.01, CH), 134.18 (d, J_{CP} 11.1, CH), 147.26 (C); m/z (ES^+) 1658 ($[C_4H_9-P(C_6H_4CH_2CH_2C_8F_{17})_3]^+$, 100%); m/z (ES^-) 79/81 (Br⁻, 100%).

5.5 References.

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Appendix



A1 Organic Postgraduate Programme Autumn/Winter 2002

Tuesday 22 nd October	Problem Session	M. Kachala & S. Gilbey
Tuesday 5 th November	Problem Session	R. Calderon & V. Salafia
Tuesday 12 th November	M. Chem Literature Discussion Sessions	Mr. T. Bell Ms. E. Gibson Mr. J. Miles Ms. R. Muir Chair: Mr. L. Olesik Main questionnaires Ms. D. Palmer Mr. R. White Mr. R. Yeomans
Tuesday 19 th November	Problem Session	G. Barth & R. Roig
Tuesday 26 th November	M. Chem Literature Discussion Sessions	Ms. D. Palmer Mr. R. White Mr. R. Yeomans <i>Chair:</i> Mr. M. Kachala <i>Main questionnaires:</i> Mr. T. Bell Ms. E. Gibson Mr. J. Miles Ms. R. Muir
Tuesday 3 rd December	Problem Session	D. Laventine & K. Weber
Tuesday 10 th December	Literature Session	Ms. K. Curtis Mr. A. Patel Ms. E. Uneyama <i>Chair:</i> Mr D Laventine <i>Main questionnaires:</i> Mr. G. Barth Mr. S. Gilbey Ms. Z. Smith
Tuesday 17 th December	Problem Session	Dr. S. Handa

A2 Organic Postgraduate Programme Winter/Spring 2003

Tuesday 11 th February	Problem Session	Dr. S. Handa
Tuesday 16 th February	Literature Session	Mr. W. Alkhuraiji Ms. K. M. Weber

		Mr. E. Kerouredan Chair: Mr. R. Calderon Main questioners Ms. K. Curtis Ms. V. Salafia Mr. G. Barth
Tuesday 25 th February	Problem Session	Mr. L. Olesik Mr. A. Patel
Tuesday 4 th March	Literature Session	Mr. G. Barth Mr. D. Laventine Mr. R. Roig Chair: Mr. R. Calderon Main questioners Mr. M. Kachala Ms. E. Uneyama Mr. A. Patel
Tuesday 11 th March	Problem Session	Ms. K. Curtis Mr. E. Kerouredan
Week 17 th -21 st March	M. Chem Project Talks	All organic M.Chem Students

A3 Conferences Attended 2002/2003

Monday 30 th October	Organic Synthesis Symposium (Loughborough)	Prof. J. Cossy (<i>Paris</i>) Prof. G. Pattenden (<i>Nott</i>) Dr. G. Lloyd-Jones (<i>Bristol</i>) Prof. P. Wender (<i>Stanford</i>)
Monday 4 th November	Leicester Half-Day Catalysis Symposium	Prof. R. Grubbs (<i>Caltech</i>) Prof. R. Sheldon (<i>Delft</i>) Prof. M. Wills (<i>Warwick</i>) Dr. D. L. Davies (<i>Leicester</i>)
Tuesday 17 th December	Sheffield Stereochemistry	Prof. M. Shibasaki (<i>Tokyo</i>) Prof. A. P. de Silva (<i>Belfast</i>) Prof. C. Bolm (<i>RWTH</i>) Prof. D. Lilley (<i>Dundee</i>) Prof. G. C. Fu (<i>MIT</i>)
Friday 13 th June	24 th East Midlands Regional Meeting Younger Members Symposium 2003	Dr. K. Altmann (<i>Novatis</i>) Dr. B. Martin (<i>Astrazeneca</i>) Dr. A. Stuart (<i>Leicester</i>) Dr. W. Golding (<i>Nott</i>) Dr. J. Thomas (<i>Sheffield</i>) Prof. J. Sanders (<i>Cambridge</i>)

A4 Organic Seminars 2002/2003

Thursday 3rd October 2002

Adventures in Chemical Biology from Non-Viral Gene Therapy to the Chemistry of Stress.

Dr. A. Miller (*Imperial College*)

Wednesday 16th October 2002

The Nucleophilic Addition/Ring closure Approach To The Synthesis of Highly Functionalised Small Molecules.

Dr. P. Perlmutter (*Monash, Australia*)

Monday 9th December 2002

The Role of Transition Metal Boryl Complexes in Catalysed Borylations Including Rhodium Catalysed C-H Bond Functionalised.

Prof. T. Marder (*Durham*)

Monday 10th February 2003

Metal Alkyne Complexes In Asymmetric Synthesis

Dr. S. Christie (*Loughborough*)

Wednesday 26th February 2003

Very Active Planar Chiral Catalysis For Asymmetric Synthesis

Dr. C. Richards (*Queen Mary*)

Monday 3rd March 2003

Exploiting the Potential of Carbon Dioxide in Synthetic Organic Chemistry

Dr. C. Rayner (*Leeds*)

Monday 17th March 2003

Molecular Design of Precursors For The CVD of Electronic Materials

Dr. C. Carmalt (*University College London*)

Monday 12th May 2003

Functionalised N-Heterocyclic Carbene Ligands In Organometallic Chemistry and Catalysis

Dr. A. Danopoulos (*Southampton*)

Monday 2nd June 2003

Shedding Light on Biological Systems: The Development of Dinuclear Lanthanide Probes

Dr S. Heath (*Manchester*)

Tuesday 3rd June 2003

Inaugural Lecture: Against Nature: Unnatural Products in the Service of Humanity

Prof. J. Percy (*Leicester*)

Monday 9th June 2003

Catalytic Asymmetric Acylation Studies Towards The Total Synthesis of Polyol Sesquiterpenes

Dr. A. Spivey (*Imperial College*)

A5 Modules and Examinations Taken in 2003

Advance Structure Determination (CH4003)

(3rd/4th Year Module, 5 Credits)

Dr. J. Malpass

Strategies in Synthetic Organic Chemistry (CH3009)

(3rd/4th Year Module, 10 Credits)

Dr. S. Handa and Dr. P. Jenkins

A6 Presentations 2003

October 2002 Group Presentation

February 2003 Literature Discussion to Organic Section

April 2003 First Year Proposal

May 2003 Group Presentation

A7 Placements in Industry 2004

3 month placement at Avecia (Huddersfield)

Supervisor: Dr. Neil Edwards.

A8 Organic Seminars 2003/2004

Monday 29th September 2003

Luminescent Supramolecular Architectures: From Shape to Function

Dr. Zoe Pikramenou, *University of Birmingham*

Monday 6th October 2003

Palladium and Platinum Metallacycles for Organic Synthesis

Dr. Chris Richards, *Queen Mary, University of London*

Wednesday 8th October 2003

NMR and Proteins

Prof. Iain Campbell, FRS *University of Oxford*

Monday 20th October 2003

Something Old, Something New, Something Borrowed and Something Blue: Complex Oxides and Sulfides.

Dr. Sandie Dann, *University of Loughborough*

Monday 27th October

Natural and Non-Natural Products: Total Synthesis and Biological Applications

Dr Chris Hayes, *University of Nottingham*

Friday 14th November 2003

Green Solvents for Catalysis

Prof. Dr. Walter Leitner,

A9 Poster Presentations 2004

September 2-3rd 2004

RSC Fluorine Conference

Poster Presentation: Fluorous Tagged Phosphonium Salts for Phase Transfer Catalysis

September 20th 2004

RSC, ORMG, Postgraduate Conference 2004 at Syngenta, Huddersfield.

Poster Presentation: Fluorous Tagged Phosphonium Salts for Phase Transfer Catalysis