CHAPTER 1
BACKGROUND AND SYNTHESIS

1.1 INTRODUCTION

The origins of crystal engineering are rooted in the understanding and control of intermolecular interactions, which include in general weak and strong hydrogen bonds, halogen-halogen interactions, π-π interactions and van der Waals forces. Although originally applied to organic solids, the field has grown to include materials that contain both organic and inorganic species [1].

In the presence of alkali halides, many thallium(I) salts and two lead(II) salts, thiourea self-assembles into molecular cages around the positive cations, which in turn is connected to each other to form highly stable, 1-d macromolecular coordination columns, with fourfold symmetry. In these columns the cations form a linear array, each in a position of eightfold coordination, with respect to sulphur atoms at the corners of a cubically distorted Archimedean antiprism. Together with the anions involved, these columns represent the basic building units of unique stoichiometric complexes.

Madelung interactions between the permanent dipole moment of thiourea, in the polarizing crystal fields of the complexes, and the positive cations have been calculated by numerical methods. The calculations show that the cohesion in the complexes is almost exclusively due to electrostatic interactions and complexing only occurs, for energetic reasons, with ionic salts, which have lattice energies less than ~160kcal/mole [2].

Space group and molar volume similarities subdivide the family into a number of groups. The largest group is complexes with formula MX.4TU (M=metal, TU=thiourea). Thallium salt complexes are easily obtainable from most thallous salts, while complexes of alkali metal salts containing doubly or triply charged anions have so far been impossible to prepare. Other non-thallium MX.4TU that have been prepared include CsBr.4TU, CsCl.4TU and RbI.4TU, to name but a few [3].

The polarizable thiourea ligand in these ionic complexes act as bridges between the separated anions and cations. Vibrational spectra of the thiourea ligand

are sensitive to structural changes and have been used extensively to obtain more information about covalent metal-thiourea coordination compounds and thiourea inclusion compounds. The appearance of an additional band would indicate the formation of a covalent metal-thiourea bond.

Interest in the chemical and physical properties of a number of Tl(I) + Thiourea complexes, L. H. W. Verhoef and J. C. A. Boeyens in 1968 [4] stimulated this study.

The main concept of their research was that ionic thiourea complexes could be synthesized that allowed cations and anions to pack into linear stacks or columns in the solid state. What they discovered was that the structure of an ionic thiourea complex is in fact determined by the anion in the complex as it is the anion that plays a vital role in the formation of the coordination columns and not the close packing of tetragonal $(M^{+}.4TU)_{n}$ columns [4]. Their reasoning in synthesizing a thallium based thiourea complex with benzoate as the anion was that the benzoate is large enough to perturb the column but not symmetrical enough to have the same effect on all sides of the column. Thallium was the metal of choice as it is known that thallous salts of the benzoate form well defined complexes with in thiourea [4].

From an extensive search of the Cambridge Database Version 5.26, also included 2005 updates during Feb., May, Aug. [5] numerous complexes involving thallium (I) and organic salts were found. However, very few were found that had complexations between organic thallium(I) salts and thiourea. The presence of thiourea constitutes an essential part of the structural framework to be investigated.

In fact only five complexes were found and all had a very noticeable similarity, all the salts possessed an $R\text{-}O^{-}$ functional group, where R represents Cl, P, C and N. This in itself was a strong indication that sulphides (R-S), nitriles (C-N) and imines (C=N) were not known to complex with thallium(I) and thiourea.

With all the above background as an initial basis to this current study, the direction and motivation of this project was to synthesize ionic thallium-thiourea complexes but with different substituted benzoates as the anions. The motivation behind this was to try and determine the role that both steric and electronic changes on the anion might have on the packing of the complex in the solid state, if any. Also the electron charge distribution of the benzene ring when bonded to various substituents could also be examined using spectroscopic techniques in the solid state, should this

result in observable and more than just subtle changes in the solid state conformations [6]. The substituents chosen, were decided upon due to their varying degrees of electron donating and withdrawing effects. Also included were anions with large bulky groups to see what effect that might have on structure, bonding and packing. While still other anions had similar but not identical properties to the benzoate ion.

All in all the anions encompass an extremely wide range of possible effects the ions might have on the properties of the complexes.

With in this study various analytical techniques will be used. Infrared and Raman spectroscopy will be made use of in order to ensure the complexes have indeed been synthesised by the presence and absence of specific bands. These techniques will also be used to investigate the possibility of hydrogen bonding with in the complexes which will be indicated by any shifting of the bands. It is expected that hydrogen bonding will be observed between the organic acid functional group and possibly the thiourea molecules.

UV spectroscopy will also be used. It will confirm the presence of the benzoic acid derivatives which should all be distinguishable by different shifting of the aromatic bands resulting from the different electronic effects caused by the various substituents. UV spectroscopy will also indicate if charge transfer reactions are taking place with in the complexes. This will be seen by the presence of an extra band.

The main intention behind using solution NMR spectroscopy will be to determine the stiochiometric ratio of the complexes as well as prove the presence of both the benzoic acid derivatives and the thiourea with in the complexes. It is also hoped that shifting of the peaks will be seen as this will indicate hydrogen bonding in solution, although this does not imply hydrogen bonding in the solid state.

The use of thermal analysis will be to identify the complexes, as it will be hoped that the various substituents of the complexes will decompose with in different temperature ranges mainly as a result of stronger or weaker inter and intramolecular forces as a result of changing the ionic character. Mass spectroscopy will be incorporated into the thermal work as analysis will be done on the complexes with in temperature ranges that correspond to the thermal events. It was expected that the identity of the leaving groups could be determined using this accurate mass facility.

Finally, all the complexes will undergo x-ray analysis. It is hoped to obtain single crystals of any complexes in order to investigate and correlate the structural

data of each. However, powder diffraction may also have to be used in the event of not all the complexes producing single crystals, mainly to study the powder patterns as an indicator of categories of similar and different crystal structures. This could assist in analysing any other data collected for comparable categories of groups of effects.

Note: The main nomenclature used throughout the thesis to describe the thallium-benzoate-thiourea complexes is the substituent of the particular complex plus the word 'complex', e.g. 2-fluoro complex.

1.2 ORGANIC SALTS FROM WHICH IONS WERE DERIVED

2-aminobenzoic acid	electron donating
3-aminobenzoic acid	
4-aminobenzoic acid	
2-nitrobenzoic acid	electron withdrawing
3-nitrobenzoic acid	
4-nitrobenzoic acid	
2-fluorobenzoic acid	weaker electron withdrawing
3-fluorobenzoic acid	
4-fluorobenzoic acid	
2-chlorobenzoic acid	
3-chlorobenzoic acid	
4-chlorobenzoic acid	
2-bromobenzoic acid	
3-bromobenzoic acid	
4-bromobenzoic acid	
2-methylbenzoic acid	similar to benzoic acid
3-methylbenzoic acid	
4-methylbenzoic acid	
4-methoxybenzoic acid	bulky group
2-hydroxybenzoic acid	
NH_4 PF_6	could accommodate 4-fold symmetry
BF_4	similar to NH_4PF_6

1.3 SYNTHESIS OF ORGANIC SALTS

The organic benzoic acid derivatives which are to be investigated can all be purchased direct from chemical distributors as was the case for this particular study. The chemical distributor was Fluka. However, it is also possible to synthesise the salts in a laboratory using basic organic chemistry techniques.

A few examples are given below :

4-aminobenzoic acid and 4-nitrobenzoic acid can be synthesized by using toluene as a starting material [7].

2-aminobenzoic acid and 2-nitrobenzoic acid are formed using the same procedure as above. This is due to the fact that direct introduction of one nitro group into toluene yields a separable mixture of the liquid 2-nitrotoluene and 4-nitrotoluene [7].

2-aminobenzoic acid can also be synthesized by the hydrolysis of phthalimide to give phthalamidic acid which then undergoes the Hoffmann reaction with the addition of NaOCl to give 2-Aminobenzoic acid [8].

3-aminobenzoic acid and 3-nitrobenzoic acid both stem from toluene. The 3-aminobenzoic acid is formed by the reduction of 3-nitrobenzoic acid [7].

The halogenated benzoic acids can be prepared relatively easily [9, 10].

1.4 EXPERIMENTAL

1.4.1 SYNTHESIS OF COMPLEXES

The same method of synthesis was used for all the complexes. However, the final method took a relatively large amount of trial and error to obtain the best possible results, i.e. ensuring optimum amounts of solvent, optimum temperatures, etc.

Before detailing the methodology, a general overview of how the complexes were to be synthesized is given :

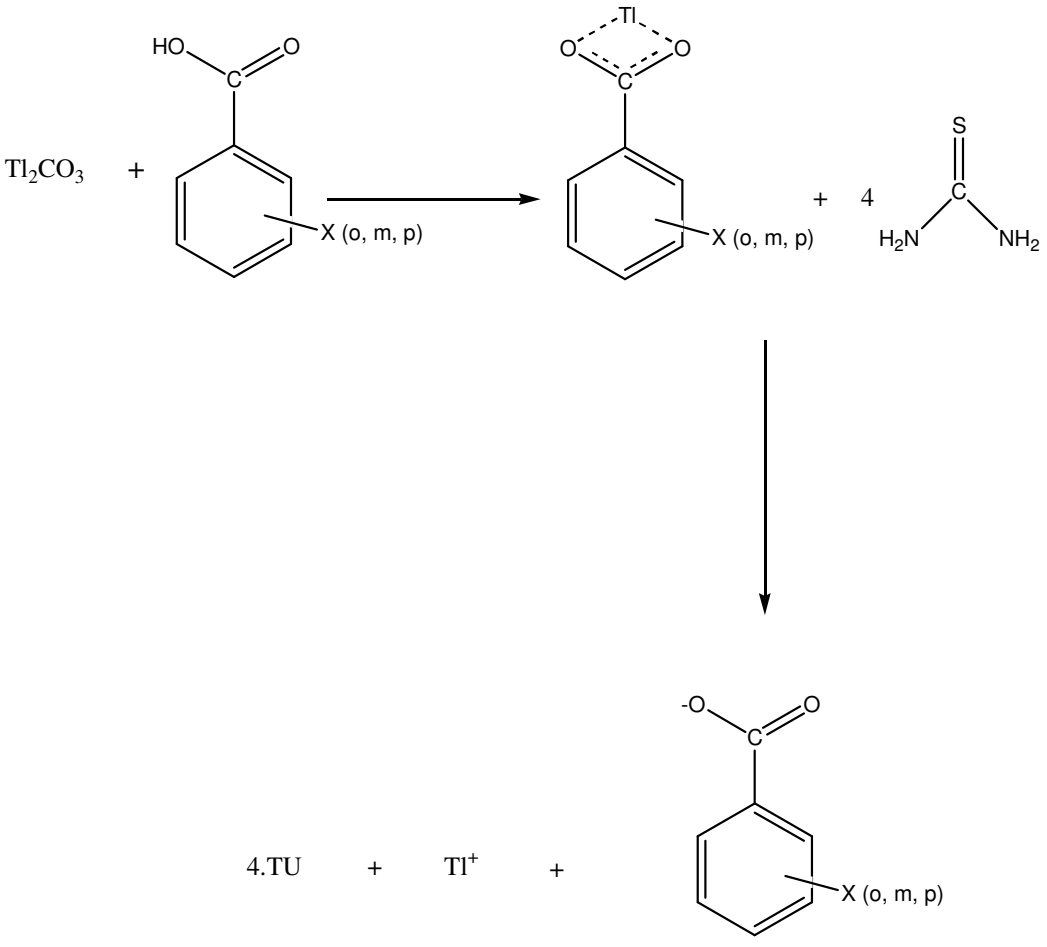

Fig. 1.1 General synthesis of complexes : X refers to the substituents listed in 1.2.

The most likely structure for the thallium benzoate intermediate would show the thallium bonded to both oxygens of the carboxylic acid with the charge being equally distributed [11]. This arrangement was also proved by the structure determination of one of the thallium benzoates isolated in this study (Chapter 2) to prove the general method and also the existence of this intermediate.

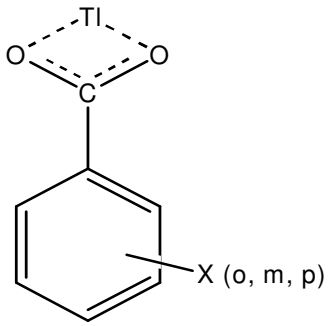

Fig. 1.2 Thallium benzoate intermediate

Before commencing this initial experiment a risk assessment of the starting materials along with the necessary safety precautions had to be taken into consideration.

Thallium, in the form of thallium nitrate ($TlNO_3$) used initially to prepare the complexes, or thallium carbonate (Tl_2CO_3) can have serious side effects. These include abdominal pain, nausea and negative effects on both the cardiovascular and nervous systems. Another notable problem is thallium's toxicity to the aquatic environment [12].

In the case of thiourea and the derivatives of benzoic acid is limited to causing irritation to skin, eyes, etc [12]. Therefore, the necessary safety precautions include wearing protective gloves and clothing, appropriate eye protection (safety glasses) and carrying out all synthesis in a fumecupboard [12].

1.4.2 EXPERIMENTAL METHOD

The standard published method of preparing the thallium benzoate complex was followed and a crystal structure of the thallium-4-aminobenzoate was determined to confirm that the method was used successfully. A total of nine different Tl (I) benzoate complexes prepared by this method from Tl_2CO_3, including *catena*-[(3,4-dimethoxybenzoato)thallium(I)] and *catena*-[(3,5-dimethoxybenzoato)thallium(I)] were recorded in the Cambridge Database [5, 11, 17].

The method involved stoichiometric amounts (1:1) of Tl_2CO_3 and the respective benzoic acid derivatives added to 60 ml of distilled water. The solutions were then allowed to boil while stirring for two hours which resulted in clear solutions. These solutions were left to recrystallise, however, as stated above, the thallium-4-aminobenzoate was the only benzoate to yield single diffraction quality crystals. The other benzoates gave precipitates. At this stage no further effort was made to attempt to recrystallise all the intermediate benzoates as this was not the focus of the study, and this literature method is well proven.

The precipitates were then redissolved in 60 ml of distilled water. The thiourea (4:1) was added, once the solutions were clear various recrystallisation methods were used in an attempt to gain single diffraction quality crystals.

1.4.3 RECRYSTALLISATION

In terms of optimum dimensions for single crystal x-ray analysis, a crystal should preferably have dimensions of approximately 0.1 mm [13].

As was stated in the experimental methodology, the crystals formed would be best described as long, thin, needle-like, white crystals whose dimensions are too small for use, and hence the reason why a great deal of time and effort was put into the challenge of obtaining larger crystals.

The initial technique that was tried was that of simply combining the dissolved starting materials then heating and stirring the precipitate along with the addition of 5ml of distilled water until all the precipitate had dissolved [4]. The temperature of the dissolved solution at this stage was 50˚C. It was then placed in a fume cupboard at

room temperature and left to recrystallise. This technique of slow cooling produced poor quality crystals in terms of size. However, the theory of slow cooling is sound as the slower a crystal grows, the lower the levels of entropy induced defects to its perfection [14]. Therefore adjustments to the slow cooling technique along with completely different methods needed to be considered.

The slow cooling variations involved allowing the dissolved mixture of starting materials to cool down at a much slower rate with the hope that larger crystals would form. Instead of dissolving the precipitate formed when the starting materials were added together at a temperature of 50˚C and leaving it to recrystallise, the dissolved precipitate was heated to 70˚C and placed in a water bath whose temperature was 65˚C. This process allowed recrystallisation to occur over a longer period of time as the solution took a relatively long time to cool.

This method turned out to be the method of choice, however, other techniques needed to be investigated in the search for bigger crystals.

Although not a new technique in itself, the above slow cooling method was repeated but with changes in both the temperatures of solution and water bath.

TEMPERATURE OF DISSOLVED SOLUTION / ˚C	TEMPERATURE OF WATER BATH / ˚C
80	80
100	90
75	70
60	50
40	30

Table 1.1 Temperatures of solution and water bath

It was found that there was no change in the crystal size whether the two temperatures were the same, varied by a few degrees, or varied by 10 degrees or more.

The next method to be tried was that of using different solvents. This entailed redissolving the formed crystals in a variety of solvents. Solvents were chosen in accordance to their dielectric constants, i.e. those with values similar to ethanol. These

included methanol, propanol and acetone. However, a variety of other solvents were also used so that a wide spectrum was covered and larger crystals had every chance of forming.

As with ethanol, these solvents required a small amount of water to be added in order for the crystals to redissolve. The ratio of water to solvent was also varied as can be seen below, all leading to the same low quality crystal.

SOLVENT	WATER : SOLVENT RATIOS
Methanol	1:1, 2:1, 5:1
DMSO	1:1, 2:1, 5:1
Acetic acid	1:1, 2:1, 5:1
Propan-2-ol	1:1, 2:1, 5:1
Acetone	1:1, 2:1, 5:1
Chloroform	1:1, 2:1, 5:1
Amyl acetate	1:1, 2:1, 5:1

Table 1.2 Ratios of water to solvent

The temperature that all the dissolved complexes were heated to was 50˚C. Once the solutions had cooled to room temperature they were then placed in the fridge for period of 2-3 hours in an unsuccessful attempt to aid recrystallisation.

As with the slow cooling technique, slight variations to the different solvent method were also tried. The main variation was repeating the synthesis of the complexes from scratch and using the various solvents in the place of ethanol each time. However, as with the other techniques this proved unfruitful.

Vapour diffusion otherwise known as isothermal distillation [15] was the next technique to be tried. The principles of this technique center around polarity. The sample is dissolved in a suitable solvent and placed in a test tube. A less polar solvent than that used for dissolving the sample is placed in a beaker. The test tube is then placed in the beaker and the beaker is sealed. The theory is that the less polar solvent

diffuses through the vapour phase into a solution of a compound in the more polar solvent and hence reducing the solubility. This slow diffusion should cause crystals to form.

The first complex to be investigated using this technique was the complex containing the 2-fluorobenzoic acid, i.e. Tl_2CO_3, TU, 2-fluorobenzoic acid. A mass of 0.005g of the complex was dissolved in a warm (60˚C) 2:1 ethanol mixture in a test tube and then placed in a beaker containing diethyl ether. The diethyl ether was not warmed as it has a boiling point of 35˚C. The beaker was then left at room temperature to se if crystals would form. Some crystals did begin to form after a period of a few hours, however, they were of poor quality.

This process was repeated several times using crystals of the 2-fluoro, thallium, thiourea complex but the solvents used were varied along with temperatures.

COMPLEX	DISSOLVING SOLVENT	LESS POLAR SOLVENT
Tl_2CO_3, TU, 2-fluorobenzoic acid	Ethanol/Water (60˚C)	Diethyl ether (RT)
	Ethanol/Water (60˚C)	Hexane (RT)
	Ethanol/Water (60˚C)	Hexane (60˚C)
	Ethanol/Water (60˚C)	THF (RT)
	Ethanol/Water (60˚C)	THF (50˚C)
	Ethanol/Water (60˚C)	Chloroform (RT)
	Ethanol/Water (60˚C)	Chloroform (50˚C)
	Ethanol/Water	CCl_4 (RT)

	(60˚C)	
	Ethanol/Water (60˚C)	CCl_4 (50˚C)

Table 1.3 Variation of solvent

As seen from the results this method did produce crystals, unfortunately initially though not of diffraction quality for single crystal diffraction. At a later stage this compound was again recrystallised and then produced usable single crystals from the mother liquor.

A variant of the vapour diffusion method is a process known as the Hanging Drop Method, this too was tried. This is normally a technique reserved for the crystallisation of macromolecules, such as proteins [16].

The principle is the same as for vapour diffusion. In this case, a drop of complex dissolved in solvent is placed in vapour equilibrium with a liquid reservoir of solvent. For equilibrium to be achieved vapour begins to leave the drop and eventually reaches the reservoir. Hence the sample increases in supersaturation. The concentration of both the complex and solvent increases as solvent leaves the drop for the reservoir. Therefore when both the drop and the reservoir have an equal concentration, equilibrium is reached [16].

The complex used in this technique was the 2-methyl complex.
Six different solvents were tested, each in a 1:1 ratio with water apart from DMSO which had a ratio of 1:5. The solvents included ethanol, DMSO, methanol, 2-propanol, DMF, amyl acetate. Saturated solutions of the complex and the various solvents were prepared. A drop of each solution was then placed on individual glass cover slides. Six different wells were then filled with the respective solvent and water ratios. Carefully the slides were placed above the relative wells and left in the hope that crystals would form.

Over a period of 2-3 days some crystals did begin to form, however, their quality was not what was hoped for. The crystals that did form were those with the DMSO/water,

ethanol/water and methanol/water. As with the other techniques the crystals were long and needle-like and much to thin for single crystal x-ray diffraction.

As has already been mentioned previously the best technique was that of slow cooling using a water bath set a few degrees below the temperature of the dissolved solution. Even though these were the best quality crystals, they were still not of sufficiently good quality for single crystal x-ray analysis to be carried out.

As another concluding note to this recrystallisation research, it must be noted that when dissolving the precipitate or crystallized material (formed when starting materials were combined) and redissolving crystals of the complexes, water is always needed for the dissolving process to occur. The only solvent that did not require water was DMSO, however, the resulting crystals were of no better quality. Water may in some way influence the growth of crystals and hence the reason why all crystals produced by all different recrystallisation methods were of such poor quality.

A total of 20 different benzoic acid derivatives, complexed with Tl^{+}.4TU, were prepared. A further two complexes with PF_6^- and BF_4^- as anions were also prepared. These complexes were subjected to the instrumental analysis described earlier. These results are described in the following chapters.

1.5 REFERENCES

CHAPTER 1

1. A. M. Beatty, CrysEngComm, 2001, **51**, 1-13
2. J. C. A. Boeyens and G. Gafner, The Journal of Chemical Physics, 1968, **49(5)**, 2435-2438
3. F. H. Herbstein and J. C. A. Boeyens, Inorg. Chem. 1967, **6(7)**, 1408-1425
4. L. H. W. Verhoef and J. C. A. Boeyens, Acta Cryst. 1969, **B25**, 607
5. The Cambridge Structural Database: a quarter of a million crystal structures and rising, F. H. Allen, Acta Crystallogr., **B58**, 380-388, 2002, Version 5.26, also included 2005 updates during Feb., May, Aug.
6. W. Lewandowski, L. Fuks, M. Kalinowska and P. Koczon, Spectrochimica Acta Part A, 2003, **59**, 3411
7. Allinger, Cava, De Jongh, Johnson, Lebel, Stevens, Organic Chemistry, 2nd ed., Worth Publishing Inc., 1976, 623-624
8. L. F. Fieser and M. Fieser, Organic Chemistry, 3rd ed., Reinhold Publishing Corporation, New York, 1956, 661
9. I. L. Finar, Organic Chemistry, The Fundamental Principles, Vol. 1, 1967, Longmans, Green and Co. Ltd, 724
10. www.orgsyn.org/orgsyn/prep.asp?prep=cv2p0299
11. Olof Kristiansson, Eur. J. Inorg. Chem., 2002, 2355-2361
12. International Chemical Safety Cards, ICSC : 0077, 0680
13. D. Boyle, www.xray.ncsu.edu/GrowXtal
14. www.oci.unizh.ch/service/cx/Crystal_Growth.pdf, page 4
15. www.ccp14.ac.uk/ccp/webmirrors/blake/~pczajb2/growcrys.htm.orig#Vapour_diffusion
16. www.hamptonresearch.com/support/pdf101/CG101HDC.pdf page 1
17. F. Wiesbrock and H. Schmidbaur, J. Am. Chem. Soc., Vol. 125, NO. 12, 2003, 3624