EXECUTIVE SUMMARY OF THE THESIS

Halogen-Bonded Complexes of N,N-Dimethylacrylamide with Iodoperfluorocarbons

TESI MAGISTRALE IN MATERIALS ENGINEERING AND NANOTECHNOLOGY – INGEGNERIA DEI MATERIALI E DELLE NANOTECNOLOGIE

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1. Introduction

The design of polymers capable of self-assembly has been the subject of intense study in the last decades, as it offers the possibility to obtain self-ordered structures with enhanced and new functionalities.

One common strategy employed in the design of self-assembled polymers involves the use of block copolymers, that are copolymers made of alternating blocks of different homopolymers. Self-organization in these polymers is driven by the low affinity between the alternating blocks. Carefully adjusting the molecular weight of each block, their volume fraction, and their functionalities, it is possible to obtain lamellar, cylindrical, spherical, and more complex structures. [1]

Non-covalent interactions also play an important role in driving polymer self-assembly, in fact, taking advantage of the specificity, geometry, strength and reversibility of these interactions it is possible to design highly functional and stimuli-sensitive materials, avoiding complex processes of covalent chemical synthesis. Therefore, tuning the structure and functionality of building modules it is possible to control at molecular level material structure, composition, morphology and dimensions, thus enabling the construction of an extensive variety of structures.

Recently halogen bonding has proven to be a powerful tool in polymer self-assembly, allowing to obtain nanostructured polymeric materials aligned up to the macroscopic scale [2]
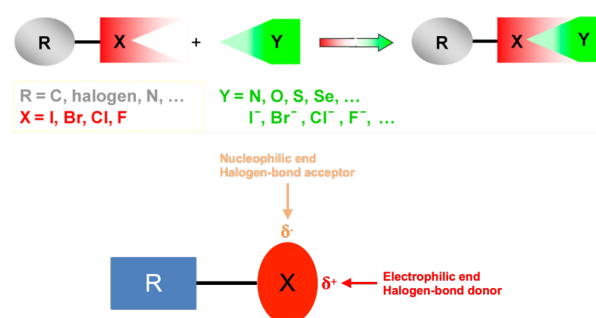
1.1 Halogen bond

Figure 1.1: Schematic representation of the halogen bond. Highlighted is the electrophilic region, the σ-hole.

The halogen bond (XB) is a non-covalent interaction involving halogen atoms as electrophilic sites. The main feature enabling the formation of XB is the presence, on covalently

bonded halogen atoms, of a region of positive electrostatic potential –the σ-hole-, focused along the extension of the covalent bond. This region can interact with nucleophilic species, resulting in highly directional interactions. XB presents some unique features that have drawn interest on its use in supramolecular chemistry: directionality, strength tunability, hydrophobicity and donor atom dimensions.

XB has been largely applied as a design element in crystal engineering, where its directionality proved to be very effective in the construction of various supramolecular architectures with different dimensionalities, complex interpenetrated networks, and porous structures.

The high directionality of XB has been successfully exploited for the design of supramolecular liquid crystals starting from non-mesomorphic components, and taking advantages from the modularity of this bottom-up approach, many functional systems, such as light-emitting, conducting, and magnetic materials have been obtained. [2]

Several studies have shown the potential of XB in the self-assembly of polymers, where it was successfully employed to obtain comb-like polymers, layer-by-layer structures and complex lamellar-within-cylinder hierarchical structures; it has been used to increase the efficiency of light responsive supramolecular polymers, in the creation of self-healing polymers and to achieve solid-state polymerization of monomer co-crystals. From literature some common strategies have emerged in the design of supramolecular polymer self-assemblies with XB, like the frequent use of poly(4-vinylpyridine) (P4VP) due to the presence of the pyridine group, an effective XB acceptor; 1,4-diiodotetrafluorobenzene is a frequently used XB donor, as are iodoperfluoroalkanes that, thanks to the strong tendency of fluorinated chains to segregate, favours the formation of ordered nanostructures. [3]

The polymer poly(N,N-dimethylacrylamide) (PDMA) has not been used yet in halogen-bonded self-assembled systems, but it has been utilised successfully in a block copolymer with poly(4-vinylpyridine) to obtain a double comb-like system through hydrogen bonding with 3-pentadecylphenol (PDP). Both blocks were able to form hydrogen bond with PDP, with the formation of two distinct microphases with different periodicity [4]. Due to the analogies between HB and XB it is expected that PDMA could also self-assemble with halogen bond donors. If this hypothesis is proved correct it will lead to a new addition to the list of polymers that can be used to design supramolecular halogen-bonded polymer self-assemblies.

To evaluate this new possibility this work focused on the characterization of the binding modes of PDMA starting from the analysis of model systems obtained upon self-assembly of the monomer N,N-dimethylacrylamide (DMA) with mono- and di-iodoperfluorocarbons. Preliminary experiments have also been carried out on halogen-bonded complexes of PDMA.

2 Materials and methods

2.1 Material design

DMA has been selected as model compound for PDMA, while both ditopic α,ω-diiodoperfluoroalkanes (DIPFn n = number of C atom in the molecule = 2, 4, 6, 8) and monotopic 1-iodoperfluoroalkanes (IPFn n = number of C atom in the molecule = 6, 8, 10) of different chain length, as well as ditopic and monotopic iodoperfluoroarenes, 1,4-diiodotetrafluorobenzene (DITFB) and iodopentafluorobenzene (IPFB) respectively, have been applied as XB donors.
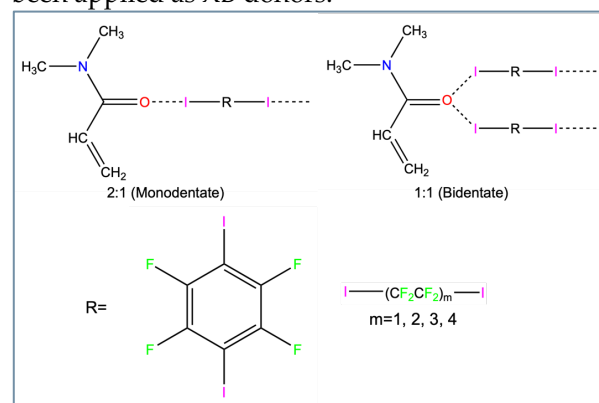

Figure 2.1: Scheme of the complexes with ditopic XB donors.

The halogen bond acceptor site is the carbonyl oxygen, which has been reported to be able to act as both a monodentate and a bidentate acceptor. In order to understand its binding mode with iodoperfluorocarbons as halogen bond donors, samples were prepared using both a 1:1 or 1:2 stoichiometric ratio (1 or 2 equivalent of iodine

atoms per carbonyl group) between XB-donor and acceptor (Fig. 2.1, 2.2).

Hydrogen bonded complexes between DMA and ethylene glycol (EG), phenol (PH) and hydroquinone (HQ) as hydrogen bond donors were also prepared for comparison. (Fig. 2.3).
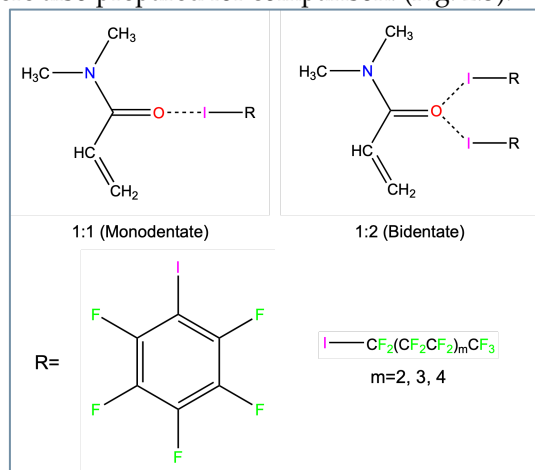

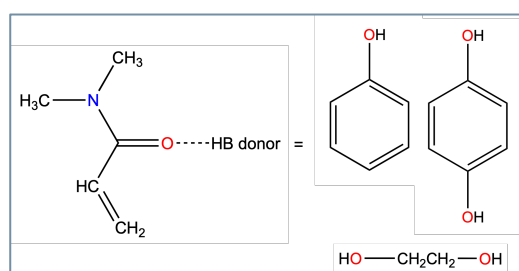Figure 2.2: Scheme of the complexes with monotopic XB donors.

Figure 2.3: Scheme of the DMA complexes with HB donors.

DMA was able to dissolve most of the iodoperfluorocarbons and EG at the stoichiometric ratios used. This allowed to prepare complexes without the use of additional solvents; for these samples the two components were simply mixed, left overnight and then analysed. The only exception were complexes with 1,4-diiodotetrafluorobenzene and 1-iodoperfluorodecane, whose preparation required to dissolve the XB-donor in CHCl₃, following with addition of DMA. The vials with the solutions were then put in jars containing paraffin oil for isothermal solvent evaporation.

It has been reported that the carbonyl may act as both XB and HB acceptor, and studies of several co-crystals between N-methylacetamide and dihalotetrafluorobenzenes showed the occurrence of orthogonal hydrogen and halogen bonds. Taking into account these data, attempts to prepare ternary complexes containing both an XB and the

"corresponding" HB donor have also been made (Fig 2.4) DMA/EG/DIPF2 was prepared by mixing directly the starting materials, while DMA/PH/IPFH and DMA/HQ/DITFB were prepared using the isothermal solvent evaporation procedure at room temperature.
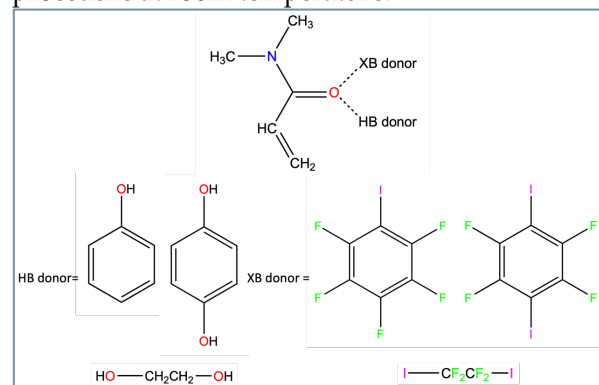

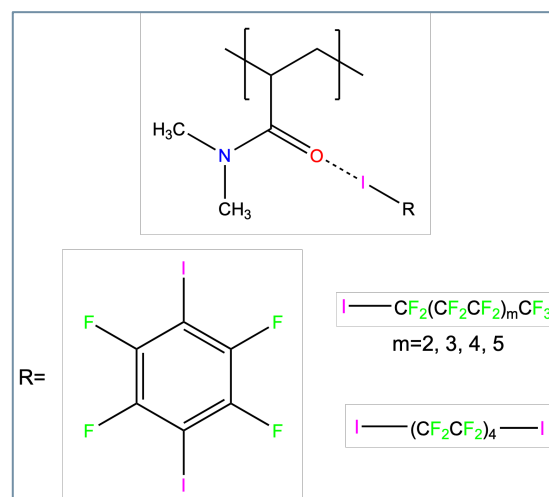Figure 2.4: Scheme of the DMA ternary complexes.

Figure 2.5: Scheme of the PDMA complexes prepared with XB donors.

Samples of PDMA with various iodoperfluorocarbons were also prepared, considering 1 equivalent of iodine atom per carbonyl group (Fig. 2.5). Different methods were used to synthetize the complexes.

The first method was the slow isothermal solvent evaporation, and was performed using IPF6, IPF10 and IPF12. PDMA and the IPFC were dissolved separately in chloroform, then the two solutions were mixed in a vial. The vial was then put in a jar containing chloroform, for solvent evaporation in atmosphere saturated with chloroform vapours; after about 3 weeks the remaining solvent was evaporated, and the obtained complexes analysed. The second method was fast isothermal solvent evaporation; the solutions were prepared similarly

to the first procedure, but the vials were just covered with parafilm in which holes were made and left under hood for solvent evaporation. IPF6, IPF8, IPF10, DITFB and DIPF8 were used.

The third method was melting; PDMA and the IPFC were mixed together. The mixture was heated at 200°C, the melting temperature of the polymer, for five minutes, then left to cool and mixed with a spatula. The process was repeated five times. In this case only IPF10, IPF12 and DITFB were used, due to the high volatility of shorter iodoperfluoroalkanes.

All the DMA complexes were characterized through differential scanning calorimetry (DSC), ATR-FTIR spectroscopy and nuclear magnetic resonance (NMR) spectroscopy.

NMR spectroscopy of the DMA/IPF10 and DMA/DITFB complexes was performed by dissolving the solid samples in deuterated chloroform, using trifluoroethanol as an internal reference; the samples where DMA acted as solvent were instead analysed without any dilution, using an external reference of deuterium oxide and trifluoroacetic acid for the lock.

The samples with PDMA were characterized through ATR-FTIR spectroscopy and thermogravimetric analysis (TGA). PDMA/IPF8, PDMA/IPF10 and PDMA/DITFB were also characterised with DSC.

3   Results and discussion

The samples prepared with DMA as solvent formed no precipitate, while with the samples prepared by isothermal evaporation of the solvent solid precipitates were obtained. Crystallization of the DMA/IPF10 solution led to the formation of a white, slightly sticky powders, and for DMA/DITFB clear, slightly yellow crystals were obtained.

DSC analysis of halogen-bonded binary complexes allowed to shed light on the correct stoichiometry between DMA and XB-donors, showing that the carbonyl group behaves as a monodentate XB-acceptor. In fact for all the complexes prepared using 1eq. of iodine atoms per carbonyl group DSC thermogram showed the presence of new melting and crystallization peaks, different from those of the starting modules, proving the formation of XB-complexes. On the contrary, in complexes prepared using 2eq. of iodine atoms per carbonyl group the presence of non-bonded

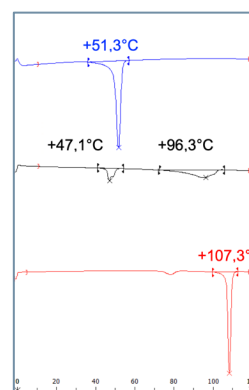perfluorocarbons was detected together with the 1:1 complex.

Figure 3.1: DSC of the DMA/DITFB samples. 1eq. sample in blue, 2eq. sample in black, pure DITFB in red.

Figure 3.1 shows the DSC curves for the DMA/DITFB 1:1 complex, in comparison with the DMA/DITFB 1:2 complex and DITFB. Melting point of pure DITFB is 107,3°. This peak is absent in the thermogram of the 1:1 complex where a new melting peak different from those of the starting materials appears at 51,3°C. This proves that the 1:1 sample is a new species rather than a mechanical mixture of the starting materials. On the contrary in the thermogram of the 1:2 sample two endothermic peaks can be seen. The first one at 47,1°C correspond to the melting of the 1:1 complex, while the second at 96,3°C is the melting of the excess of DITFB, which appears at lower temperature due to the melting point depression caused by its impurity.

FTIR spectroscopy is another useful technique to probe the occurrence of XB. In fact, XB interaction between molecules is always accompanied by changes of IR spectra of complex relative to that of each starting module. We focused on the analysis of complexes prepared using 1eq. of iodine atom per carbonyl group, and results are reported in Table 3.1. In all the spectra it was possible to observe peak shifts for the DMA. In particular the C=O stretching peak at 1647,47 cm^{-1} in pure DMA is red-shifted while the C-N stretching at 1417,16 in pure DMA is blue-shifted upon formation of the complexes: this further confirms the occurrence of a XB involving the carbonyl group. The larger shifts were observed in the DMA/DITFB complex. Regarding the DMA/DIPFAs complexes the shifts decreased with longer perfluorocarbons chains, from 4,5 to 2,7 cm^{-1}. The samples with monotopic XB donors showed smaller shifts (Table 3.2), suggesting that the ditopic ones are more efficient in the formation of the complex.

Table 3.1: FTIR spectroscopy peaks and shifts of the C=O and C-N stretching of the DMA in the complexes with ditopic XB donors.

Sample	$\tilde{v}$ C=O (cm^{-1})	$\delta\tilde{v}$ C=O (cm^{-1})	$\tilde{v}$ C-N (cm^{-1})	$\delta\tilde{v}$ C-N (cm^{-1})
Pure DMA	1647,47	-	1417,46	-
DMA/DITFB	1639,88	-7,59	1419,93	2,47
DMA/DIPF2	1643,72	-3,75	1418,95	1,49
DMA/DIPF4	1644,05	-3,42	1419,82	2,36
DMA/DIPF6	1644,66	-2,81	1420,11	2,65
DMA/DIPF8	1644,79	-2,68	1420,52	3,06

Table 3.2: FTIR spectroscopy peaks and shifts of the C=O and C-N stretching of the DMA in the complexes with monotopic XB donors.

Sample	$\tilde{v}$ C=O (cm^{-1})	$\delta\tilde{v}$ C=O (cm^{-1})	$\tilde{v}$ C-N (cm^{-1})	$\delta\tilde{v}$ C-N (cm^{-1})
Pure DMA	1647,47	-	1417,46	-
DMA/IPFB	1645,48	-1,99	1419,49	2,03
DMA/IPF6	1646,69	-0,78	1420,94	3,48
DMA/IPF8	1647,35	-0,12	1421,09	3,63
DMA/IPF10	1646,67	-0,8	1421,46	4,00

A similar red shift for the carbonyl group of DMA has been observed for complexes with EG, HQ, and PH, confirming the formation of HB between the oxygen of the carbonyl and the OH group.

Complexes liquid at room temperature were also analysed through ^{19}F-NMR spectroscopy, which further confirmed the occurrence of XB. We focused on the CF$_2$-I group, which upon XB undergo the larger shift of chemical shift (δ). The CF$_2$-I group in pure DIPF2 (dissolved in pentane-no XB) was found at -52,48 ppm, while in the complex DMA/DIPF2 the same signal was shifted up-field at -56,82 ppm. This is clear evidence of the occurrence of XB. The same behaviour was observed in all the spectra of the samples with iodoperfluoroalkanes, with differences in chemical shifts ranging from 4,3 through 6,1 ppm up-field. The resonances of the other fluorine atoms showed small or no shifts at all, confirming that the observed up-field shifts are due to the formation of XB; the shifts of the monotopic and ditopic iodoperfluoroalkanes with same length were comparable. (Table 3.3)

Table 3.3: ^{19}F chemical shifts of the IPFC of the liquid complexes.

Sample	δ -CF$_2$- in n-pentane (ppm)	δ -CF$_2$- in DMA (ppm)	$\Delta\delta$ -CF$_2$- (ppm)
DMA/DIPF2	-52,48	-56,82	4,34
DMA/DIPF4	-58,16	-63,66	5,5
DMA/DIPF6	-58,4	-64,03	5,63
DMA/DIPF8	-58,17	-64,28	6,11
DMA/IPF6	-58,84	-64,66	5,82
DMA/IPF8	-58,97	-64,13/-64,93	5,16/5,96

The DMA/IPFB complex showed smaller up-field shifts, for all the aromatic fluorine atoms, the larger shift being the one of fluorine atom in para-position with respect to iodine, suggesting that this might be due to a charge redistribution over the whole ring following the formation of the interaction. The solid complexes, DMA/IPF10 and DMA/DITFB showed small changes in chemical shifts, but their analyses were made in solution with chloroform-d, so the results are only indicative on the formation of the interaction.

The ternary solutions of DMA/EG/DIPF2 and DMA/PH/IPFB did not show any formation of precipitate, while the DMA/HQ/DITFB showed formation of elongated crystals inside a red liquid phase. In all the solutions IR spectroscopy showed the red-shift of the C=O of DMA, and peak shifts could be identified for both the HB donor and the XB donor; analysis of the crystals found in the DMA/HQ/DITFB sample showed that they consisted of the DMA/DITFB binary complex. DSC showed fusion peaks corresponding to the binary halogen-bonded complex, and small crystallization peaks corresponding to non-bonded iodoperfluorocarbons. This suggests that in each of the three samples the halogen-bonded complex is present, and while it is not possible to determine if the hydrogen-bonded one has also formed, it is possible to exclude the formation of the ternary ones.

Synthesis of the PDMA complexes gave similar results with both the slow and fast isothermal evaporation processes; IR spectroscopy showed slightly larger red-shifts of the carbonyl stretching for the samples obtained with the slow process, suggesting that better complexation was achieved with this method. The melting procedure could be discarded: the mixture assumed a yellow/orange

tint during the process, and smaller IR shifts with respect to the other methods suggest degradation of the samples.

FTIR spectra for all the samples show the typical red-shift of the carbonyl band, confirming the formation of the complexes between polymer and Iodoperfluorocarbons. For all the samples TGA show that water that is usually absorbed by the highly hygroscopic PDMA is not present in the XB-complexes, suggesting that water has been substituted by the iodoperfluorocarbon upon XB complexation, and meaning that the halogen bond is able to prevail on the hydrogen bond.

PDMA/IPF8 complex is an amorphous solid and no melting peaks could be observed in the DSC analysis, however the absence of fusion or crystallization peaks associated to free IPF8 confirms the purity of the sample. PDMA/IPF10 showed a small fusion peak at 62,8°C, but since the melting point of pure IPF10 is at about 66°C it is not possible to confirm that what has been measured is the peak of the complex. The PDMA/DITFB sample had a small melting peak at 48,5°C, and the peak of pure DITFB at 107°C was not visible; this lower melting point is compatible to what was observed in the model with DMA and confirms the formation of the complex.

4   Conclusions

The preparation and characterization of the model system of N,N-dimethylacrylamide with iodoperfluorocarbons have been performed with positive results. DSC showed the appearance of new fusion and crystallization peaks, and it was possible to determine that the oxygen of the carbonyl acts as a monodentate XB acceptor site. The occurrence of XB interaction was confirmed through IR spectroscopy, where red-shifts of the carbonyl peak and blue-shifts of the C-N bond indicated formation of the bond between iodine and the oxygen; moreover, larger shifts of those peaks were observed with the diiodoperfluorocarbons showing that the ditopic XB donors achieve better complexation than the monotopic ones. With ^{19}F-NMR of the pure liquid complexes the peaks of the fluorine atoms closer to the iodine atom showed large, up-field shifts, further proof of the formation of the interaction. Concerning the ternary samples, presence of the halogen-bonded complex and excess of IPFCs was observed with DSC, and while DMA, the HB donor, and the XB donor all show some peak shifts in IR spectroscopy, it can be concluded that DMA is not able to form ternary complexes, but instead that the halogen-bonded binary complex and maybe the hydrogen-bonded one have formed.

Preliminary studies with PDMA also suggest that the interaction was present with all the iodoperfluorocarbons.

This master thesis work has successfully shown through various characterization techniques that in the model system with DMA halogen bond is formed with a variety of iodoperfluorocarbons.

Further characterization could be made on this model, and photopolymerization experiments could be attempted on both the liquid and the solid complexes to observe how the halogen bond with iodoperfluorocarbons of different lengths influence molecular weight, polydispersity, tacticity, and structure of the final polymer.

The formation of the complex between PDMA and IPFCs have also been confirmed, and to the best of my knowledge no reports on the self-assembly of PDMA with iodoperfluorocarbons through XB are present in literature, thus the results drawn from this work open new possibilities in the design of halogen-bonded supramolecular polymer systems.

Bibliography

[1]   O. Ikkala and G. Ten Brinke, *Science (80-.).*, vol. 295, no. 5564, pp. 2407–2409, 2002, doi: 10.1126/science.1067794.

[2]   G. Cavallo *et al.*, *Chem. Rev.*, vol. 116, no. 4, pp. 2478–2601, 2016, doi: 10.1021/acs.chemrev.5b00484.

[3]   R. Kampes, S. Zechel, M. D. Hager, and U. S. Schubert, *Chem. Sci.*, vol. 12, no. 27, pp. 9275–9286, 2021, doi: 10.1039/d1sc02608a.

[4]   M. Faber *et al.*, *Macromolecules*, vol. 46, no. 2, pp. 500–517, 2013, doi: 10.1021/ma302295v.

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