$CaCl_3^-$ or Ca_2Cl_4 Complexing Cyclic Aromatic Amide. Template Effect on Cyclization

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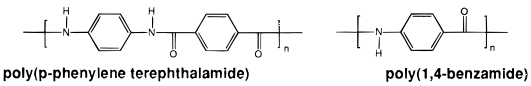
Successful manufacturing of aromatic polyamides (aramides) has been manifested only after realization of improved polymer solubility by alkali or alkali earth metal salts. Not only does the solubility of polymers like poly(*p*-phenylene terephthalamide) or poly(1,4-benzamide) increase in an amide solvent with a small amount of LiCl or $CaCl_2$ but the presence of these salts in the polymerization solvent is indispensable for successful polymerization.[1] In spite of the profound importance of the effect, the mechanistic understanding of the nature of the ionic interaction with the polymer, however, is still ambiguous.



An amide group exhibits amphiphilic properties in dipolar or H-bonding interactions; the carbonyl group is a dipole donor, while the N−H group is an acceptor.[2] It is not obvious, therefore, how the amide groups of amide solvents and polymers may participate in ion−dipole interactions. On the basis of an IR study with a LiCl and dimethyl acetamide (DMAc) solvent, Panar et al. proposed that the Cl^- ion associates with the N−H group of the polymer through hydrogen bonding to create a negatively charged polyamide, which in turn is solvated with Li^+-complexed DMAc.[3] In this proposal, the aliphatic amide carbonyl group was proposed as the sole donor, whereas the aromatic amide N−H group was proposed to be an acceptor. In order to further elucidate the nature of this interaction, we have studied complexation of a model aromatic polyamide with $CaCl_2$ in amide solvents.

To simplify the interaction site, we have employed the cyclic aromatic amide **I** as a model compound.[4] High-dilution cyclization, where a toluene solution of isophthalic acid chloride (ICl) and a DMAc solution of *m*-phenylenediamine (MPD) were added concurrently to DMAc, gave a moderate yield of **I**. The matrix-assisted laser desorption ionization (MALDI) mass spectroscopy of the crude product confirmed the existence of cyclic products in addition of linear oligomers. MALDI also revealed that the smallest and most abundant cyclic oligomer was the hexamer (Figure 1). Cyclic hexamer[5] crystals containing $CaCl_2$ were isolated from a DMAc/$CaCl_2$ solution of the crude reaction mixture. The salt can be readily washed out with water, but then the free cyclic hexamer is practically insoluble in all organic solvents.

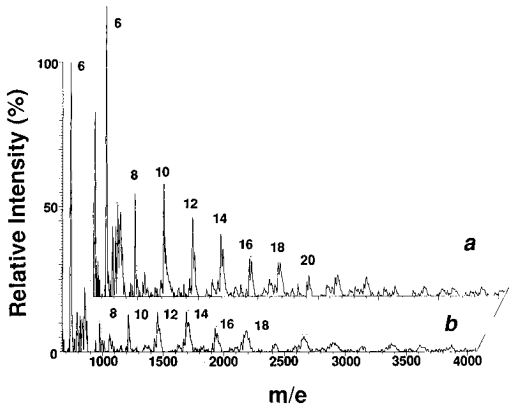
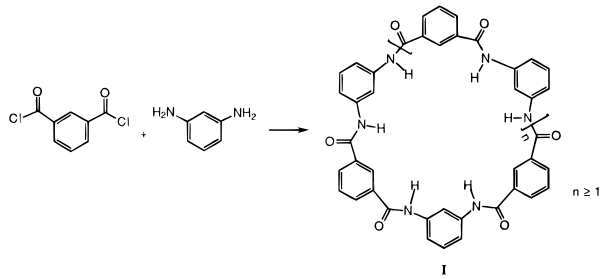


Figure 1. MALDI-TOF mass spectroscopy of a crude reaction product of ICl and MPD under high-dilution conditions. By using indolacrylic acid in DMSO as the matrix for MALDI, cyclic products could be selectively ionized. (a) Reaction in the absence of $CaCl_2$. (b) Reaction in the presence of 1 equiv of $CaCl_2$ with respect to the amide group.



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The structure of the product was further confirmed by X-ray crystallography. Single crystals were obtained under two sets of conditions from amide solutions containing $CaCl_2$, one as colorless plates (crystal A) from a supersaturated DMAc solution, and the other as colorless flat needles (crystal B) from a diluted DMF solution by slow infusion of THF. For comparison, platelet single crystals of $CaCl_2(DMAc)_4$ were also analyzed. These highly solvated crystals decomposed rapidly with loss of solvent molecules. Therefore, crystals were mounted in the presence of supernatant solvent on a Rigaku imaging plate autodiffractometer (RAXIS) equipped with a rotating anode Mo Kα source. Due to the existence of a temperature-dependent phase transition, data were collected at 0 °C. Cell parameters obtained by the R. Jaconson autoindexing routine (BLIND) method are presented in Table 1. The structure (Figure 2a) revealed by direct methods (MULTAN) for crystal A showed the chain conformation cyclic hexamer, with all the amide bonds in the trans configuration and all the hydrogen atoms of the amide group pointing inward. The structure also shows a complexation of $CaCl_3^-(DMAc)_3$ in the inner cavity, in which all three chlorides are hydrogen bonded to the six hydrogen atoms of the cyclic hexamer through H···Cl^-···H bonds. The negative charge of the complex is balanced with one Ca^{2+} ion located between two cyclic units linked via amide oxygen. Crystal B (Figure 2b) shows two molecules of cyclic hexamer formed around $Ca_2Cl_4(DMF)_4$ with one pair of oxygen atoms of the amide unit turned inward to complex to the 7-coordinate Ca ion.[6] The remaining four carbonyl groups point out and hydrogen bond to adjacent dimers. In addition, as there are internal N−H···Cl interactions, the overall appearance of the molecule is one of a cyclic amide wrapped Ca_2Cl_4. Six

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(4) A positive aspect of a cyclic compound is that it possesses no end groups and only a few complexing sites. High molecular symmetry may allow easy crystallization. Negatively, it represents only one ideal conformation.

(5) Upon dissolution of the pure $CaCl_2$ complex in d_7-DMF, two sets of NMR peaks (1:4) appear in either ^1H or ^{13}C NMR, showing the dynamic nature of the complexation. Addition of more $CaCl_2$ causes the smaller peaks to disappear. ^1H NMR (300 MHz; ppm in d_7-DMF, TMS): 7.416 (t, J = 8.3 Hz), 7.714 (t, J = 7.7 Hz), 8.029 (d, J = 1.5 Hz), 8.076 (dd, J_1 = 8.2 Hz, J_2 = 1.9 Hz), 8.262 (dd, J_1 = 7.7 Hz, J_2 = 1.5 Hz), 9.296 (s), 10.910 (s). ^{13}C NMR (ppm in d_7-DMF, TMS): 114.13, 117.89, 126.65, 128.78, 129.37, 135.44, 140.32, 170.36.

(6) A coordination number of 7 is common for a Ca binding with "α-chelation". See, for example: Doxsee, K. M.; Ferguson, C. M.; Wash, P. L.; Saulsbery, R. L.; Hope, H. *J. Org. Chem.* **1993**, *58*, 1557.

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Table 1. Selected Cell Parameters and Bond Distances of Crystals

crystals	symmetry	cell parameters	bond	distance (Å)
$CaCl_2(DMAc)_4$	monoclinic, $P2_1/n$	$a = 9.7029(2)$ Å	Ca−Cl	2.789
		$b = 12.105(4)$ Å		
		$c = 10.296(3)$ Å		
		$\beta = 96.63(2)°$	$Ca-O_{DMAc}$	2.296−2.313
crystal A	triclinic, $P\bar{1}$	$a = 12.498(2)$ Å	Ca−Cl	2.711−2.750[a]
		$b = 22.729(3)$ Å		
		$c = 12.342(2)$ Å		
		$\alpha = 99.457(6)°$	$Ca-O_{DMAc}$	2.259−2.320
		$\beta = 105.796(11)°$		
		$\gamma = 75.345(9)°$		
crystal B	monoclinic, $C2/m$	$a = 13.984(1)$ Å	Ca−Cl	2.841−2.847
		$b = 32.014(1)$ Å		
		$c = 13.533(1)$ Å		
		$\beta = 96.63(2)°$	$Ca-O_{DMF}$	2.354
			$Ca-O_{Cyclic}$	2.474

[a] Reference 11.

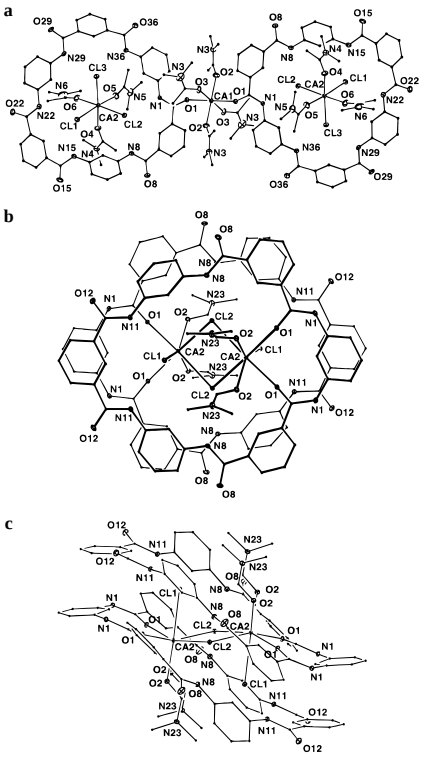

Figure 2. Crystallographic structure of crystal A (a) and top (b) and side views (c) of crystal B.

THF molecules were found to be packed interstitially. LiCl was also found to enhance the solubility of the cyclic amide, but several attempts at cocrystallization have been unsuccessful. It is noteworthy that even though a large number of anion-binding cyclic compounds are known,[7,8] a cyclic host molecule that exhibits both anion and cation binding is uncommon.

The LiCl-complexed structure proposed by Panar et al. is in agreement with the structure of crystal A, but the structure of crystal B demonstrates the possibility of the aromatic carbonyl oxygen being able to participate in the Ca^{2+} binding.[9] In general, salts appear to increase the solubility of polyamides by interrupting the hydrogen-bonding interaction of the amide groups, thus preventing formation of typical β-sheet-like structures of *p*-aramides.

Table 2. Cyclization of MPD and ICl in NMP Solvent[a]

salt	salt wt (g)	[salt]/[amide]	wt of complexed crystals (g)
no salt			1.395
$CaCl_2$	2.775	0.500	1.354
$CaCl_2$	8.324	1.500	1.922
LiCl	2.120	1.000	0.700
$MgCl_2$	4.761	1.000	0.000
$FeCl_3$	8.110	1.000	5.305

[a] ICl weight = 10.151 g. MPD weight = 5.407 g. Solvent volume = 300 mL.

Since the cyclic hexamer seems to be an ideal host molecule for various $CaCl_x^{(x-2)-}$ species, we investigated the possibility of template effects[10] of various salts in the cyclization. MALDI of the crude mixture revealed that cyclization in the presence of $CaCl_2$ gave a higher yield of cyclic hexamer relative to other cyclic compounds compared to cyclization in the absence of $CaCl_2$. The template effect was estimated by the amount of cyclic hexamer that crystallized from the reaction mixture. The results are summarized in Table 2. In general, cyclizations in *N*-methylpyrrolidone (NMP) with salts which could readily form an octahedral complex seem to improve the yield. The use of early main group salts and less than 1 equiv of $CaCl_2$ has an adverse effect on the cyclization. This could be a result of formation of complexes with the linear oligomeric intermediate which does not provide a conformation favorable for cyclization.

In conclusion, we have found that an aromatic amide group may interact with $CaCl_2$ as either a dipole donor or acceptor, and a certain complex anion $CaCl_x^{(x-2)-}$ may render a template effect on the formation of cyclic aramides.

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Supporting Information Available: X-ray structure coordinates of cyclic crystals (A and B) and $CaCl_2(DMAc)_4$ and ^1H and ^{13}C NMR spectra (23 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, can be ordered from the ACS, and can be downloaded from the Internet; see any current masthead page for ordering information and Internet access instructions.

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