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SELECTIVE RECOGNITION OF ROTAXANES FOR AN ALKALI METAL ION

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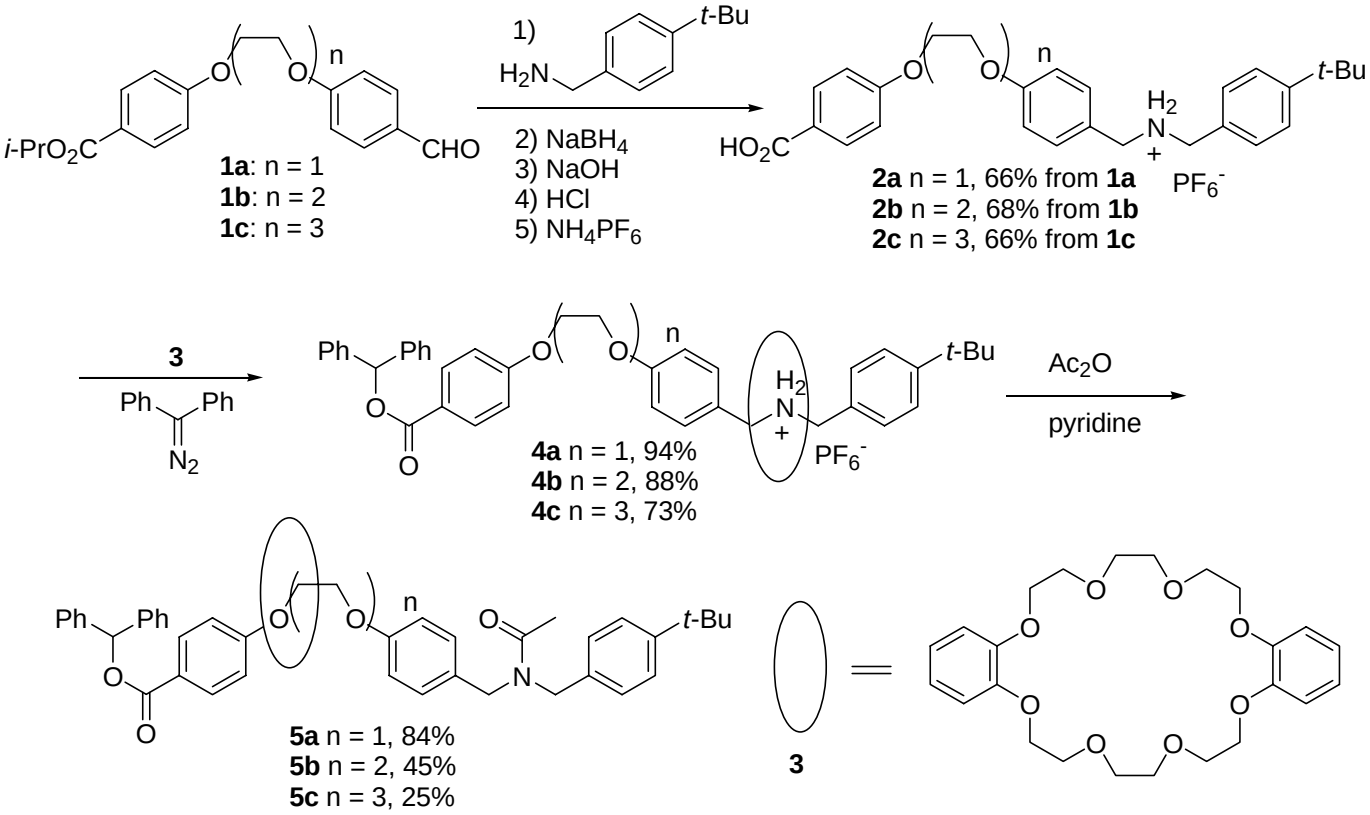
Abstract – Rotaxanes possessing a crown ether as a wheel group and oligo ethylene glycol units in the dumbbell group were synthesized using hydrogen bonding guided self-assembly and diphenyldiazomethane ester forming end-capping of pseudorotaxanes. The selective recognition of the lariat-crown-like rotaxanes for lithium ion was discovered. That recognition depended on the number of ethylene glycol units.

Numerous macrocycles have been synthesized to develop receptors for selective metal cations. A relationship exists between the cavity size, cationic radius, and stability of the resulting complex. [1] Several approaches were employed for improvement of metal ion selectivity and binding. Crown ethers were functionalized with pendant arms containing an additional coordinating group. Moreover, a new class of molecules, cryptands, was designed. Cryptands serve as effective receptors, moving crown ether into the third dimension. The lariat crowns and the cryptands generally possess higher binding constants and metal ion selectivity than regular crowns. [2]

Rotaxanes are characterized by their unique structures and properties. [3] A major research goal of its utility is to develop a molecular switch to regulate dynamic features such as shuttling, pirouetting, and unthreading in response to chemical and physical stimuli. [4] Metal-ion-selective regulation of the dynamics is a fruitful approach that uses the rotaxane system, which has more than two different types of coordination site in the axle portion. [5] Therefore, research into the cation-binding property of rotaxanes is important to develop new molecular switches. [3,6] Herein we report the selective recognition of a lariat crown-like rotaxane for metal cation and a difference of cation-binding property by regulation of the number of ethylene glycol units in the axle.

Synthesis of the intermediates, ammonium salts (**2**) possessing a different number of ethylene glycol units, used in the procedure began with condensation of aldehydes (**1**) between the benzylamine to generate the

corresponding imines. The reduction of imines, followed by hydrolysis and salt formation then produced the ammonium salts (**2**), which possess bulky aryl groups on one end and carboxylic acid groups at the other. The synthesis of rotaxanes was achieved by our method. [7] Accordingly, complexation of ammonium salts (**2**) with dibenzo24crown8 (**3**) followed by reaction with diphenyldiazomethane gave expected rotaxanes (**4**) in high yields. As an initial experiment, ^{1}H NMR spectral experiments of $CDCl_3$, DMSO-d_6, and acetone-d_6 solutions of **4** with excess amounts of $LiPF_6$ or $NaPF_6$ were performed, respectively, but no shifting for rotaxane signals was observed in the ^{1}H NMR spectra. It is likely that the rotaxanes (**4**) prefer the hydrogen binding between wheel and axle parts to coordinating between metal ions and multi glycol ethers, even though excess amounts of metal ions existed. Acetylation of rotaxanes (**4**) was carried out to cleave the hydrogen bond between wheel and axle parts, [8] corresponding acetylrotaxanes (**5**) were obtained (Scheme 1). [9]



Scheme 1.

Next, ^{1}H NMR spectroscopy was employed to monitor the addition of lithium ion to rotaxanes (**5**). The ^{1}H NMR (500 MHz, CD_3CN) spectrum of a mixture of **5a** and $LiPF_6$ revealed that **5a** did not complex $LiPF_6$. In contrast, marked shifting of signals was observed in the ^{1}H NMR spectrum of a mixture of **5b** and $LiPF_6$. The signals assigned by NOE and Roesy NMR spectra, signals, δ 3.84, 3.86, 3.89, 4.12, 4.14, 4.46, and 4.48 ppm, attributed to aliphatic protons of axle parts apparently downfield-shifted in addition of $LiPF_6$ to a solution of rotaxane (**5b**) (Figure 1). The downfield-shifted signals, δ 3.32-3.53, assigned to aliphatic protons of wheel part were also observed with addition of $LiPF_6$. A Job plot demonstrated that

the complex of **5b** with $LiPF_6$ has 1 : 1 stoichiometry in solution (Figure 2). The association constant, [10] K = 260 M^{-1}, was calculated using the Benesi-Hildebrand method. [11] In the same manner, 270 M^{-1} in the complexation of $LiPF_6$ were estimated by **5c** (Table 1). NMR titrations were employed to analyze solvent effects and the selective recognition of **5b** for alkali metal ions: the association constants, 64 M^{-1} in acetone-d_6 (run 3) and 35 M^{-1} between **5b** and Na^+ (run 4) were obtained.

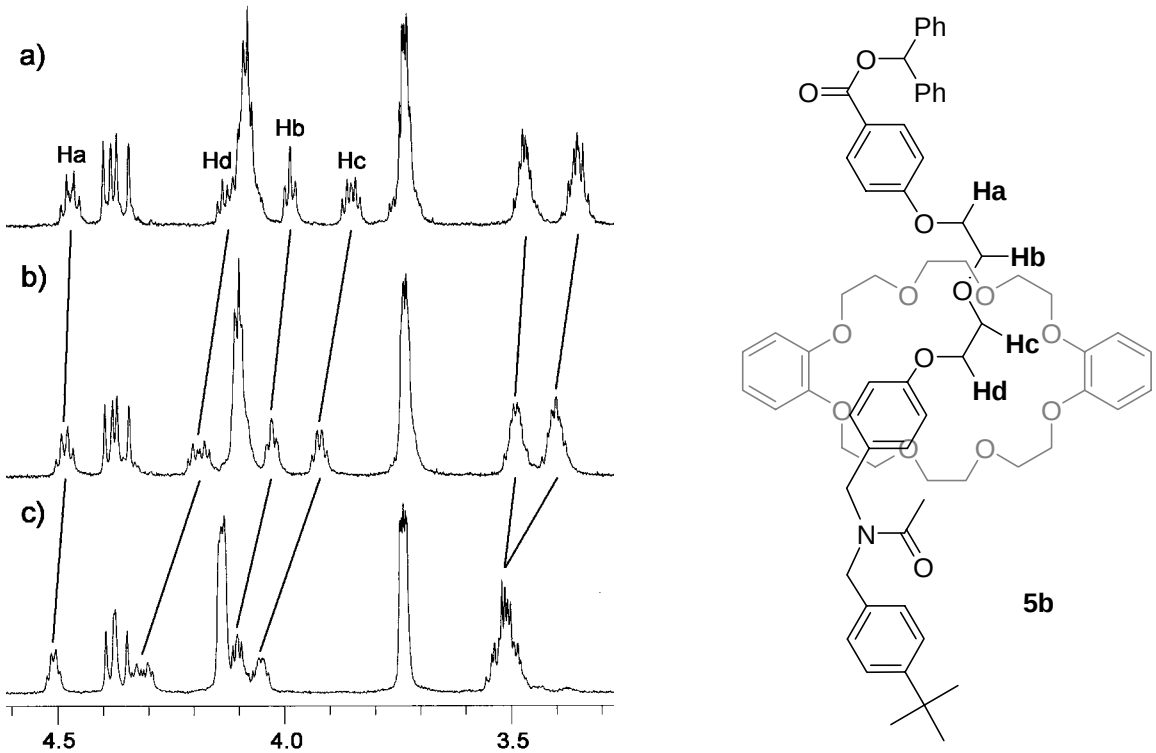


Figure 1. Partial ^1H NMR spectra (500 MHz, CD_3CN) of a) 2.0 mM of **5b**, b) 2.0 mM of **5b** and 1.5 mM of $LiPF_6$, c) 2.0 mM of **5b** and 20.0 mM of $LiPF_6$.

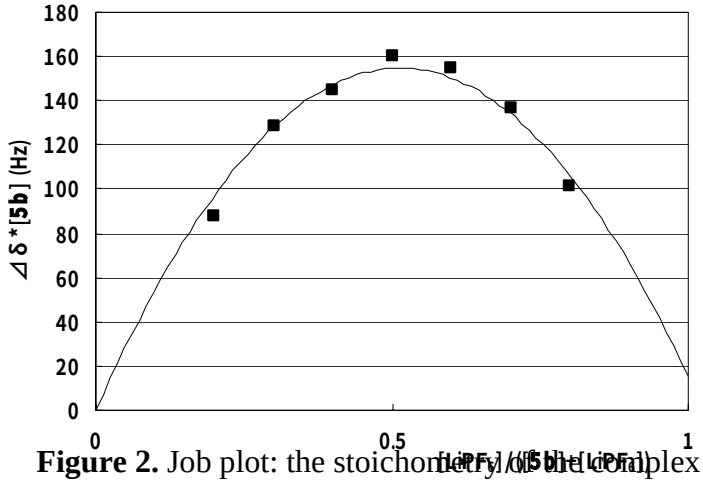


Figure 2. Job plot: the stoichiometry of the complex between **5b** with $LiPF_6$ in CD_3CN solution using data for Hd of **5b**. [**5b**] + [$LiPF_6$] = 10 mM.

Table 1. Associate constant of rotaxane with metal cation [a]

run	rotaxane	solvent	additive	K mol^{-1}
1	**5a**	CD_3CN	$LiPF_6$	
2	**5b**	CD_3CN	$LiPF_6$	260 ± 39
3	**5b**	acetone-d_6	$LiPF_6$	64 ± 29
4	**5b**	CD_3CN	$NaPF_6$	35 ± 4
5	**5c**	CD_3CN	$LiPF_6$	270 ± 33

[a] at 25°C.

The cavity between the wheel and the axle parts, similar to three dimensional recognition site of the lariat crown, might recognize the alkali metal ions because there were observation of down-field-shifted signals assigned to ethylene glycol units in **5b** and no observation of the complex (**5a**-Li^+). Molecular models of simplified complexes were calculated. Those models show that the cavities are capable of including lithium and sodium ions (Figure 3).

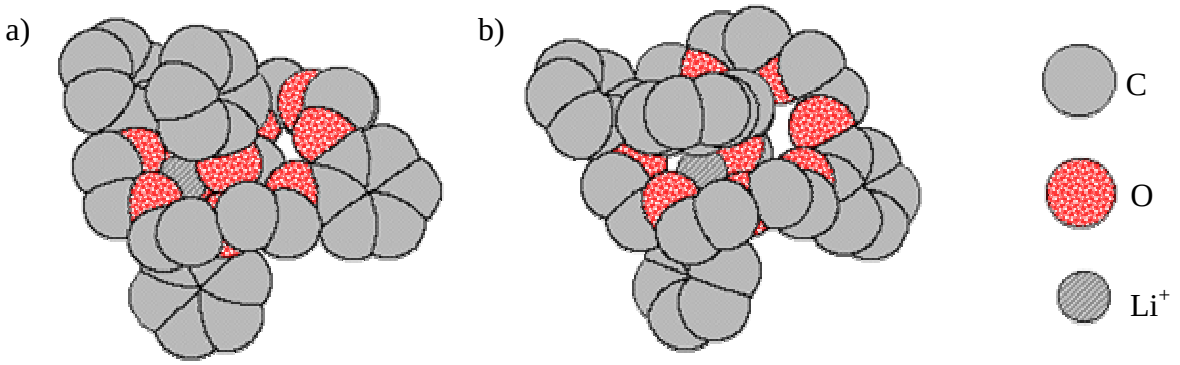


Figure 3. Molecular models of simplified complexes of Li^+ and rotaxanes; a) a model of Li^+-DB24C8-$PhOCH_2CH_2OPh$ complex, b) a model of Li^+-DB24C8- $PhO(CH_2CH_2O)_2Ph$ complex

Why does different selectivity of recognition occur among the rotaxanes? Disagreement of recognition between **5a** and **5bc** suggests three possibilities: (1) more than two ethylene glycol units in the axle must make sufficient space to recognize a lithium ion; (2) more than three coordinating atoms are required to form a stable complex; (3) oxygen atoms of alkyl aryl ether do not have sufficient ability to coordinate because of their low basicity. We could not conclude until now, molecular model, however, does not support the first interpretation: the cavity size of **5a** has sufficient space to include a lithium ion. Disagreement of recognition might be attributable to multiple oxygen atoms and their coordination ability.

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8. Selected data for acetyl rotaxanes; **5a** : ^{1}H NMR (500 MHz, $CDCl_3$) δ: 1.31 and 1.33 (s*2, 9H), 2.169 and 2.172 (s*2, 3H), 3.34-3.50 (m, 8H), 3.75-3.85 (m, 8H), 4.07-4.19 (m, 8H), 4.23-4.35 (m, 2H), 4.42-4.48 (m, 2H), 4.57-4.68 (m, 2H), 4.77-4.86 (m, 2H), 6.76-6.94 (m, 12H), 7.03-7.18 (m, 5H), 7.23-7.44 (m, 12H), 7.80-7.86 (m, 2H). IR ν max (KBr) cm^{-1}: 3433, 3032, 2874, 1713, 1605, 1508, 1454, 1254, 1057. MS (FAB): m/z = 1090($M+H^+$). **5b**: ^{1}H NMR (500 MHz, $CDCl_3$) δ: 1.31 and 1.33 (s*2, 9H), 2.18 and 2.19 (s*2, 3H), 3.32-3.54 (m, 8H), 3.75-3.92 (m, 10H), 3.95-4.08 (m, 2H), 4.08-4.23 (m, 8H), 4.28-4.37 (m, 2H), 4.42-4.44 (m, 4H), 6.80-6.95 (m, 11H), 7.01-7.22 (m, 6H), 7.25-7.45 (m, 12H), 7.87-7.94 (m, 2H). IR ν max (KBr) cm^{-1} : 3422, 2874, 1713, 1605, 1508, 1454, 1254, 1053. MS (FAB): m/z = 1134 ($M+H^+$). **5c**: ^{1}H NMR (500 MHz, $CDCl_3$) δ: 1.31 and

1.33 (s*2, 9H), 2.186 and 2.194 (s*2, 3H), 3.28-3.38 (m, 4H), 3.41-3.51 (m, 4H), 3.53-3.63 (m, 4H), 3.72-3.83 (m, 10H), 3.85-3.91 (m, 2H), 4.16-4.20 (m, 10H), 4.30-4.37 (m, 2H), 4.43-4.53 (m, 4H), 6.80-6.92 (m, 9H), 6.94-7.01 (m, 2H), 7.03-7.10 (m, 3H), 7.12-7.17 (m, 1H), 7.21-7.44 (m, 14H), 7.86-7.95 (m, 2H). IR ν max (KBr) cm^{-1}: 3425, 2874, 1713, 1605, 1508, 1454, 1254, 1053. MS (FAB): m/z = 1138 ($M+H^+$).

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