Cation complexation of quinocrown ethers in electrospray ionization mass spectrometry. A comparison with benzocrown ethers

Akihiko Tsuda,[a] Hiroshi Moriwaki[b] and Takumi Oshima *[a]

[a] *Department of Materials Chemistry, Graduate School of Engineering, Osaka University, Machikaneyama 1-16, Toyonaka, Osaka 560, Japan*
[b] *Osaka City Institute of Public Health & Environmental Science, 8-34 Tojo-cho, Tennoji Osaka 543-0026, Japan*

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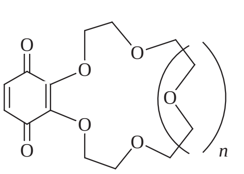
The alkali metal complexation of 15- to 18-membered ring quinocrown ethers **Q15–18**, 18- and 24-membered diquinocrown ethers **DQ18,24**, and 18-membered quinobenzocrown ether **QB18** is compared with that of the corresponding benzocrown ethers **B15–18** and dibenzo crown ethers **DB18,24** in electrospray ionization mass spectrometry (ESI-MS). The quinocrown ethers exhibit lower cation affinity than the benzocrown ethers, although the two crown series essentially show the same ion selectivity except 18-membered **DQ18** which preferentially binds Na^+. The reduced binding ability of the quinocrowns is interpreted in terms of the deformation of the crown rings by the steric repulsion with the quinone carbonyls as well as the electron withdrawing ability of the fused quinone.

Introduction

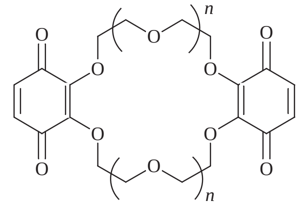
Since the pioneering work of Pedersen,[1] the cation binding ability of crown ethers has attracted much attention and numerous studies have been performed that are reported in many papers and summarized in reviews and books.[2] During recent years, much effort has been expended in order to clarify the host–guest complexation of crown ethers by mass spectrometry (ESI,[3] FAB,[4] CI,[5] PD[6], *etc.*). Electrospray ionization mass spectrometry (ESI-MS) in particular was found to be a powerful analytical method for the characterization and identification of these ion complexes and is now being increasingly employed for an assessment of these complexation behaviors.[7–11]

In a previous paper, we have reported that diphenyl-substituted 11- to 20-membered ring crown ether acetals show selective cation complexation for alkali metal ions and NH_4^+ in ESI-MS.[8] Their reduced binding ability was rationalized by considering the ring-contracted deformation, the hydrophobic effects of the diphenyl group and the poor solvation energies of the complexes.

Here, we will extend the ESI-MS analysis to the quinone-fused 15- to 24-membered ring crown ethers, **Q15–21**, **DQ18,24** and **QB18** (abbreviated hereafter as quino-15-crown-5 **Q15**, quino-18-crown-6 **Q18**, quino-21-crown-7 **Q21**, diquino-18-crown-6 **DQ18**, diquino-24-crown-8 **DQ24**, and quinobenzo-18-crown-6 **QB18**, according to generally accepted convention) to explore the effects of the fused quinone on their cation binding ability as compared with the corresponding 15- to 24-membered benzocrown ethers **B15–21** and **DB18,24** (benzo-15-crown-5 **B15**, benzo-18-crown-6 **B18**, benzo-21-crown-7 **B21**, dibenzo-18-crown-6 **DB18**, and dibenzo-24-crown-8 **DB24**).



Q15 *n* = 1
Q18 *n* = 2
Q21 *n* = 3



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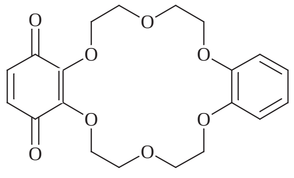
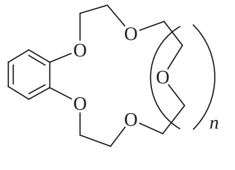
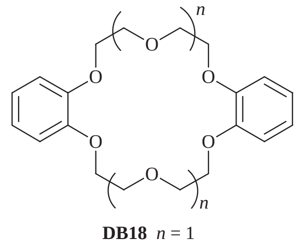


QB18



B15 *n* = 1
B18 *n* = 2
B21 *n* = 3



DB18 *n* = 1
DB24 *n* = 2

Results and discussion

Cation complexation of quinocrown ethers and benzocrown ethers

The first set of ESI-MS experiments was carried out in a methanol solution containing a crown (0.1 mM) and a mixture of five alkali metal perchlorates (each 0.1 mM). In these measurements, major mass peaks attributable to the 1 : 1 ion–crown complexes were observed along with those of the 1 : 2 ion–crown complexes for rather small membered crown ethers (**Q15** and **B15** for monofused crowns and **DQ18**, **QB18**, and **DB18** for difused crowns). In all measurements, the bare alkali metal ions and solvated metal ions were more or less detected. A representative ESI-MS spectrum for cation complexation of **DQ18** is shown in Fig. 1. To assess the selective cation binding ability, the relative intensities (I_M) of ESI mass spectra of the 1 : 1 and 1 : 2 ion–crown complexes were obtained for each crown by dividing the respective peak height by that of the most intense base peak. Isotope corrections were applicable to the

Table 1 Peak intensity data for ESI-MS analysis for complexation of crown ethers with alkali metal ions[a]

Complex[b]	n	Relative intensity I_M(%)[c] Li	Na	K	Rb	Cs
Quinocrown ethers						
$[(\mathbf{Q15})_n\cdot M]^+$	1	31	100	92	25	12
	2	(0)	(0)	(42)	(8)	(0)
$[(\mathbf{Q18})_n\cdot M]^+$	1	8	46	100	72	36
$[(\mathbf{QB18})_n\cdot M]^+$	1	9	71	100	45	17
	2	(0)	(0)	(8)	(29)	(18)
$[(\mathbf{DQ18})_n\cdot M]^+$	1	21	100	61	40	25
	2	(0)	(0)	(15)	(37)	(18)
$[(\mathbf{Q21})_n\cdot M]^+$	1	21	44	80	100	70
$[(\mathbf{DQ24})_n\cdot M]^+$	1	12	51	95	100	70
Benzocrown ethers						
$[(\mathbf{B15})_n\cdot M]^+$	1	10	100	61	28	11
	2	(0)	(0)	(22)	(10)	(4)
$[(\mathbf{B18})_n\cdot M]^+$	1	3	24	100	49	7
$[(\mathbf{DB18})_n\cdot M]^+$	1	6	35	100	44	19
	2	(0)	(0)	(0)	(15)	(8)
$[(\mathbf{B21})_n\cdot M]^+$	1	9	18	73	100	79
$[(\mathbf{DB24})_n\cdot M]^+$	1	9	57	81	100	81

[a] Solvent: methanol; crown ether (0.1 mM) and metal ion (each 0.1 mM). [b] Counter anion perchlorate was omitted. M = Li, Na, K, Rb or Cs as indicated. [c] The values in parentheses are the I_M for 1 : 2 ion–crown complexes.

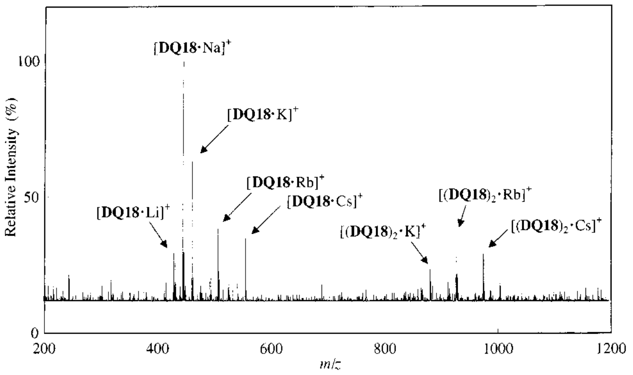


Fig. 1 ESI mass spectrum of diquino-18-crown-6 **DQ18** binding M^+ (= Li^+, Na^+, K^+, Rb^+, Cs^+). [**DQ18**] = 0.1 mM, [$MClO_4$] = 0.1 mM, solvent; methanol.

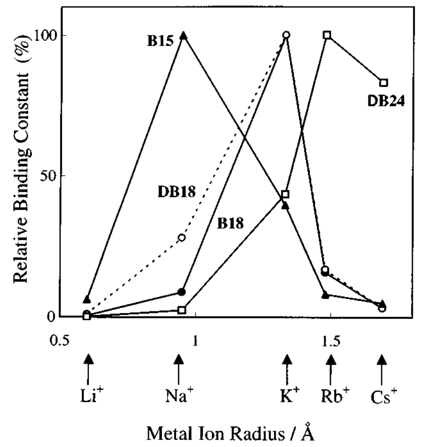


Fig. 2 Plot of relative binding constant *vs.* metal ion radius for 1 : 1 benzocrown–ion complexes (ref. 2*c*,*e*); **B15** benzo-15-crown-5, **B18** benzo-18-crown-6, **DB18** dibenzo-18-crown-6, **DB24** dibenzo-24-crown-8.

experimental data for Li^+, K^+ and Rb^+ complexes. The data set is summarized in Table 1.

Here, some attention needs to be drawn to whether the relative peak height can be used to suggest the metal–host selectivity. The quantification of the ESI-MS peak intensity of the complexes remains unclear, since the desolvation process is highly dependent on the solvation energy of each of the ionic species as well as on the needle biased voltage. For example, a possible misinterpretation of the ESI-MS data was reported for the cyclodextrin inclusion of amino acids and small peptides.[9] In contrast, for the complexations of crown ether or cryptand with alkali metal cation, several workers argued that the peak intensities of the respective complexes in the gas phase have a good correlation to their actual complex stability constants in solution.[10] Very recently, however, Liu *et al.* reported for the lariat crown ethers that the calibration for the relative cationization efficiencies of the metallated crown is essential for comparison of the selectivities in the metal–crown interactions.[11]

For the quinocrown ethers, we have no evidence for the validity of the ESI-MS for a quantitative estimation of the cation selectivities from the relative intensities I_M. The thermodynamic data for cation complexation of quinocrown ethers are not known, though the log K values for the corresponding benzocrown ethers are reported.[2c,e] These situations prompted us to compare the plots of the relative K_{rel} *vs.* metal ion radius (Fig. 2) with the corresponding plots of I_M (Fig. 3) (*vide infra*). It was found that the K_{rel} profile of each benzocrown ether very closely resembles the corresponding I_M profile. Keeping this in mind, we employed I_M to at least qualitatively represent the selective cation binding ability.

The 1 : 1 ion–crown complexes

The metal ion responsible for the 1 : 1 base peak (I_M = 100) was Na^+ for quino-15-crown-5 **Q15** and diquino-18-crown-6 **DQ18**, K^+ for quino-18-crown-6 **Q18** and quinobenzo-18-crown-6 **QB18**, Rb^+ for quino-21-crown-7 **Q21** and diquino-24-crown-8 **DQ24**. Here it should be noted that the 18-membered diquinocrown **DQ18** binds Na^+ in preference to the expected K^+. On the other hand, for the benzocrown series, the 1 : 1 base peak was observed at Na^+ for benzo-15-crown-5 **B15**, at K^+ for benzo-18-crown-6 **B18** and dibenzo-18-crown-6 **DB18**, and at Rb^+ for benzo-21-crown-8 **B21** and dibenzo-24-crown-8 **DB24**, respectively. These selective cation binding properties can be more explicitly visualized in the comparative plots of I_M *vs.* metal ion radius (Å) for the same membered crowns (Fig. 3a–d). The cation selectivities of the benzocrowns **B15**, **B18**, **DB18**, and **DB24** based on the ESI-MS data were also essentially compatible with the actual complex stabilities determined by the other measurements commonly employed,[2c,e] *e.g.*, calorimetry, conductivity, ion selective electrode, potentiometry, and NMR (Fig. 2).

The binding profile of quino-15-crown-5 **Q15** is similar to that of the benzo-15-crown-5 **B15** except for reduced Na^+/K^+ selectivity for **Q15** (Fig. 3a). These crowns are too large to envelop the smallest alkali metal ion Li^+ (ionic radius 0.60 Å)[12] by considering the cavity radius (0.86–1.1 Å)[13] for **B15**. The maximal peaks at Na^+ (ionic radius 0.95 Å)[12] are probably due to the size-fitted ion-in-the-hole complex.[14] A decrease as the ion radius increases from Na^+ to Cs^+ (K^+ 1.33 Å, Rb^+ 1.48, Cs^+ 1.69)[12] is related to the decreasing binding ability with the increasing ion radius. For these larger cations, **Q15** and **B15** would exhibit mass spectra attributable to the "nesting" complexes or the less-favorable "perching" ones.[15] The poor Na^+/K^+ selectivity of **Q15** as compared with **B15** may be due to the decrease in the absolute binding ability of **Q15**. In practice, **Q15** showed lower complexation ability towards K^+ than **B15** (*vide infra*).

These effects of quinone fusion can be rationalized by the strong electron accepting ability as well as the much enhanced distortion of crown ring. In the PM3 calculations[16] for these two crowns, the most striking difference is the unfavorable steric effect of the quinone carbonyls which induce the adjacent

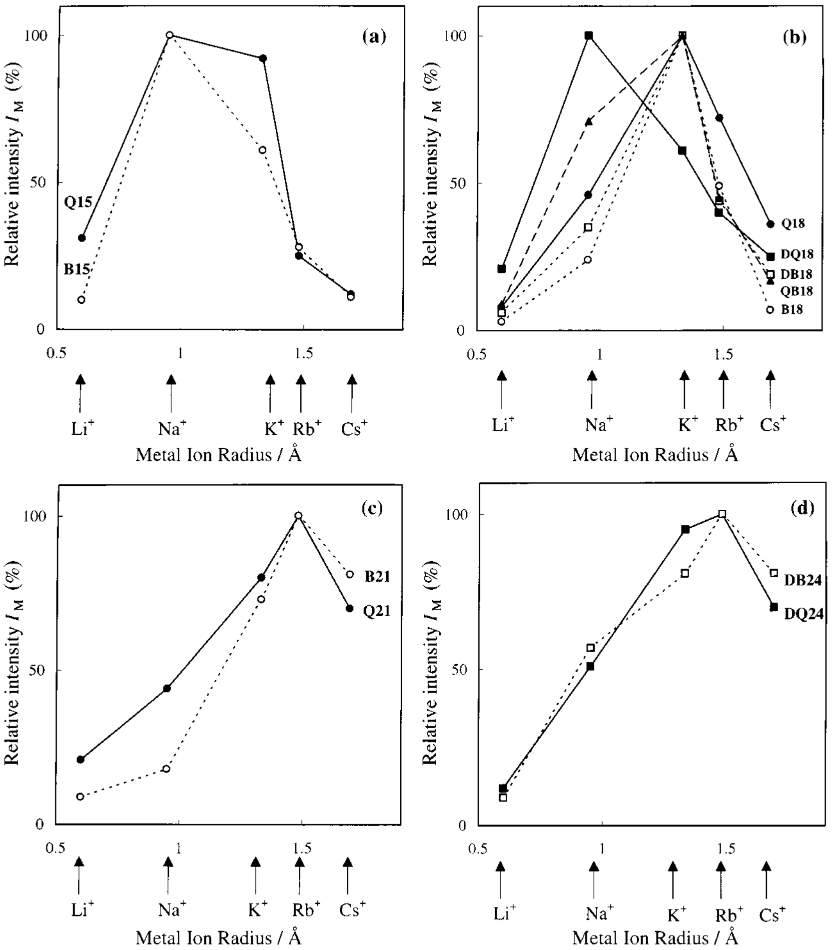


Fig. 3 Plots of relative intensity (I_M) of ESI mass spectra *vs.* metal ion radius for 1:1 crown–ion complexes; (a) **Q15** quino-15-crown-5 and **B15** benzo-15-crown-5; (b) **Q18** quino-18-crown-6, **DQ18** diquino-18-crown-6, **QB18** quinobenzo-18-crown-6, **B18** benzo-18-crown-6 and **DB18** dibenzo-18-crown-6; (c) **Q21** quino-21-crown-7 and **B21** benzo-21-crown-7; (d) **DQ24** diquino-24-crown-8 and **DB24** dibenzo-24-crown-8.

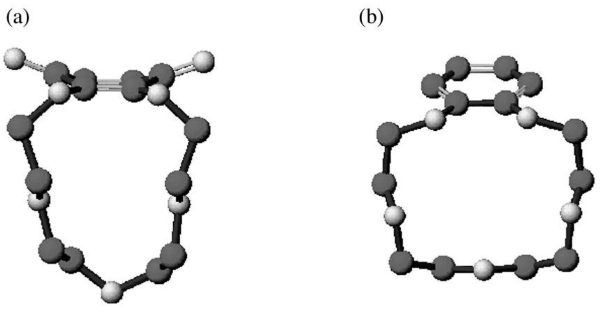


Fig. 4 View of the molecular structure of (a) **Q15** quino-15-crown-5 and (b) **B15** benzo-15-crown-5. Hydrogens have been omitted for clarity.

oxyethylene units to adopt an extraordinary flipped-out structure with respect to the quinone moiety (Fig. 4). The torsion angles (θ) across the conjunct C–O bonds are calculated to be much larger for **Q15** (57 and −56°) than for **B15** (23 and −23°). The calculated distances between the facing oxygen atoms range from 3.8 to 6.2 Å for **Q15** and from 4.6 to 5.1 Å for **B15**, respectively. Such a constrained and folded ring deformation was realized in the X-ray structure analysis of **Q15**,[17] although the comparable **B15**[18] is known to adopt a quasi-rectangular crystalline conformation. As a result, **Q15** seems to adopt a bent ellipsoidal structure narrowing the effective ring cavity, whereas **B15** has a rectangular one (close to square).

These structural features caused by fused quinone rings also seem to be the case for all quinocrowns and more or less result in the deformation of the ring to reduce the complexation ability. Such a steric hindrance seems to be one of the reasons for our finding that an attempt to synthesize the lower quino-12-crown-4 instead gave the dimeric diquino-24-crown-8 **DQ24** (see Experimental section).

As for the 18-membered crown ethers investigated, the base peak was attained as expected, at K^+ with the exception of diquino-18-crown-6 **DQ18**, which gave the base peak at Na^+ (Fig. 3b). The shift of the base peak cation to the smaller Na^+ is ascribed to the substantial decrease in the effective ring cavity of **DQ18** as compared with the other 18-membered crowns (cavity radius of 1.3–1.6 Å).[14] The abnormal binding behavior of **DQ18** must therefore be caused by the double quinone constraint which exerts additive steric effects on the crown ether ring, even more diminishing the conformational freedom of the ring cavity. Among the four K^+ selective crowns, their selectivity for this cation seems to decrease in the order **B18** > **DB18** > **Q18** > **QB18**. Benzocrowns **B18** and **DB18** provided similar binding profiles regardless of the number of fused benzenes, although quinocrown **Q18** exhibited less selective complexation. The K^+ selectivity, furthermore, decreases in the case of quinobenzocrown **QB18** compared with that of **Q18**. These findings imply that even monoquinone-fusion brings about a more noticeable reduction in the binding selectivity as well as in its affinity, and the increasing ring rigidity by fusion of an additional benzene ring to the quinocrown ring results in the enhancement of this effect.

Quino-21-crown-7 **Q21** gave a base peak at Rb^+ similarly to benzo-21-crown-7 **B21** (Fig. 3c). Ambiguity in predicting which cation, Rb^+ or Cs^+, is more preferentially bound by the 21-membered ring crown compounds can be seen (cavity radius 1.7–2.15 Å).[14] The vagueness in observing a more selective cation would be due to more increased ring flexibility owing to the incorporation of one additional oxyethylene unit as compared with the 18-membered crown compound. The two crowns **Q21** and **B21** showed similar binding plots except for the somewhat higher deviation of **Q21** for the smaller Li^+ and Na^+. The reduced Na^+/Rb^+ selectivity for **Q21** is probably due to the intrinsic poor binding affinity as described in the later section. A straightforward application of the size-fitted ion-in-the-hole concept is no longer enough to account for the complexation of a highly flexible large ring compound like **Q21**, in which the incorporated cation can be bound by the wrapping or capsulating coordination of ring oxygen atoms.[19]

Diquino-24-crown-8 **DQ24** and dibenzo-24-crown-8 **DB24** also gave base peaks at Rb^+, in which these two crowns showed very similar binding profiles (Fig. 3d). **DB24** is reported to have a comparable binding affinity for K^+–Cs^+ probably because of the highly flexible crown ring. Though small, the steric effect of double quinone-fusion appears in the binding profile of **DQ24** as compared with **DB24**. One can easily see a slight rise and drop of I_M for the smaller K^+ and the larger Cs^+, respectively. Such opposite deviation around Rb^+ may be accounted for by the decrease in the effective ring cavity of **DQ24** as experienced for the diquino-18-crown-6.

The 1 : 2 ion–crown complexes

The 1 : 2 ion–crown complexes were observed mainly for the smaller 15-membered quino- and benzocrowns **Q15** and **B15**, and 18-membered diquino-, quinobenzo-, and dibenzocrowns **DQ18**, **QB18** and **DB18**. The values of I_M are given in parentheses in Table 1. The formation of such multiple-complexes is general for a variety of crowns with a relatively smaller ring size.[20] The 1 : 2 maximum peak tended to appear at the next largest alkali metal ion than that responsible for the 1 : 1 base complexes. This shift was also the case for the 1 : 2 complexes of diphenyl-substituted crown ether acetals, previously reported.[8] Here, an exception is that diquino-18-crown-6 **DQ18**, which gave a 1 : 1 base peak at Na^+, gave the maximum 1 : 2 peak at the next largest Rb^+. The irregularity of **DQ18** infers that the actual ring cavity is not reduced to a size comparable to the 15-membered ring, thereby this diquinocrown can sandwich the originally expected Rb^+. It is also noteworthy that the quinocrowns provide a maximum 1 : 2 peak (I_M) about twice as large as do the corresponding benzocrowns. Of further interest is that the ratio of 1 : 2 ion–crown complexes, in comparison with 18-membered crown ethers, also increases in the order **DB18** < **QB18** < **DQ18**, though the monosubstituted 18-membered crowns **Q18** and **B18** do not give these possible 1 : 2 complex peaks. Apparently, as described above, the fusion of quinone distorts the crown ring more effectively than that of benzene. Furthermore, the double fusion of quinone or benzene is responsible for the more effective decrease in the ring cavity, being suitable for multiple-complexation.

Relative binding affinities of crown ethers towards K^+

Next we examined the complexation of a mixture of quinocrowns and benzocrowns towards the selected K^+ in order to know the binding abilities. The ESI-MS mass spectra of the 1 : 1 K^+–crown complexes were considerably weaker for quinocrowns than for the corresponding benzocrowns (Table 2). The most intensive peak (taken as the base peak $I_M = 100\%$) is observed for **B18**, the weakest one ($I_M = 4\%$) for **DQ18**. The I_M ratios of benzocrown to quinocrown varied in the range of about 2–17. It is noted here that the di-fused crowns gave rather high I_M ratios of 5–17 as compared with 2.3–4.6 for the mono-fused crowns. This means that double quinone fusion brings about the remarkable drop in the binding ability. Within a series of crowns, the mono-fused 18-membered ring provided the strongest peak as expected from the ion-in-the-hole concept.[14]

Table 2 Peak intensity data for ESI-MS analysis for complexation of a mixture of crown ethers with K^+ [a]

Relative intensity I_M(%)					
1 : 1 Complex [b]				1 : 2 Complex [b]	
$[\mathbf{Q15}\cdot K]^+$	9	$[\mathbf{B15}\cdot K]^+$	21	$[(\mathbf{Q15})_2\cdot K]^+$	7
$[\mathbf{Q18}\cdot K]^+$	22	$[\mathbf{B18}\cdot K]^+$	100	$[\mathbf{Q15}\cdot\mathbf{B15}\cdot K]^+$	3
$[\mathbf{QB18}\cdot K]^+$	17			$[(\mathbf{B15})_2\cdot K]^+$	2
$[\mathbf{DQ18}\cdot K]^+$	4	$[\mathbf{DB18}\cdot K]^+$	68		
$[\mathbf{Q21}\cdot K]^+$	14	$[\mathbf{B21}\cdot K]^+$	61		
$[\mathbf{DQ24}\cdot K]^+$	8	$[\mathbf{DB24}\cdot K]^+$	40		

[a] Solvent: methanol; crown (0.1 mM) and metal ion (each 0.1 mM). [b] Counter anion was omitted.

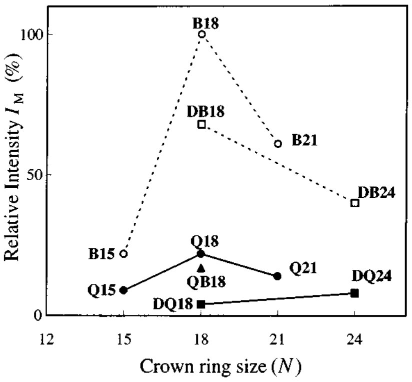


Fig. 5 Plots of relative intensity (I_M) of ESI mass spectra *vs.* crown ring sizes (N: numbers of ring atoms) for 1 : 1 crown–K^+ complexes; **Q15** quino-15-crown-5, **Q18** quino-18-crown-6, **Q21** quino-21-crown-7, **DQ18** diquino-18-crown-6, **DQ24** diquino-24-crown-8, **QB18** quinobenzo-18-crown-6, **B15** benzo-15-crown-5, **B18** benzo-18-crown-6, **B21** benzo-21-crown-7, **DB18** dibenzo-18-crown-6, and **DB24** dibenzo-24-crown-8.

The K^+ binding ability can be more definitely shown by the plots of I_M *vs.* the crown ring size for the 1 : 1 complexes (Fig. 5). For mono-fused crowns, familiar profiles were observed for both series of crowns, with the maximum peak at the K^+ fitted 18-membered ring. However, the quinocrowns apparently showed poor binding affinity towards this metal ion. Furthermore, incorporation of two quinones or a couple of quinone and benzene groups brought about the astonishing drop in the affinity of **DQ18**, **DQ24** as well as **QB18**. These characteristic properties are again due to the steric deformation of quinocrown rings in addition to the electron-withdrawing ability of the acceptor quinone.

Besides the homogeneous dimers, where both crowns are the same, heterogeneous dimers consisting of two different crowns were also detected between **Q15** and **B15** (Table 2). The I_M intensity is several times higher for quinocrowns **Q15** than benzocrown **B15**. The absence of a possible dimer complex for **DQ18** is explained by its greatly lowered binding ability.

Conclusion

In the present ESI-MS study, we have found that 15- to 21-membered monoquinocrown ethers **Q15–21**, 18- and 24-membered diquinocrown ethers **DQ18,24** and 18-membered quinobenzocrown ether **QB18** exhibit cation selectivities for the 1 : 1 and 1 : 2 bound complexes with alkali metal ions. The cation selectivities were essentially the same as those of the corresponding benzocrown ethers. The only exception was the 18-membered diquinocrown ether **DQ18** which provided the maximum 1 : 1 ion–crown mass peak at Na^+, although the corresponding dibenzocrown **DB18** preferentially bound K^+. All the quinocrown ethers were found to be inferior to the corresponding benzocrowns in binding affinities for alkali metal cations. These binding behaviors of quinocrowns were attributable to the steric repulsion and the electron withdrawal of the fused quinone moiety which will bring about the deformation of the crown ring as well as the mitigation in the ion–dipole interaction.

Experimental

Melting points were measured with a Yanagimoto melting-point apparatus and were uncorrected. NMR spectra were recorded on a JEOL EX-270 spectrometer in a $CDCl_3$ solution using tetramethylsilane (TMS) as an internal standard. IR spectra were recorded on a JASCO FT/IR-300E spectrometer. Mass (EI) spectra were determined with a JEOL JMS-DX303 spectrometer and a SHIMADZU GCMS-QP200A gas chromatograph mass spectrometer. ESI-MS was performed on a HITACHI M-1200 AP ES mass spectrometer equipped with a standard electrospray ion source. The drift and needle voltage was set to 60 and 3000 volts, respectively. A 70 °C N_2 gas was used for the desolvation of charged droplets. The nebulizer temperature was 180 °C. Solutions containing crowns (0.1 mM) and metals (each 0.1 mM) were infused into the ion source in a continuous flow at about 1 ml min^{-1} with a syringe pump. Elemental analyses were performed on a Yanaco CHN corder MT-5. Molecular structures were calculated by PM3, MOPAC Version 94.10 in CAChe, Version 3.7, CAChe Scientific, 1994.

Materials

All alkali metal perchlorates were extra pure and were used without further purification. Spectrally pure methanol (Dojin Co. Ltd) was used in sample solutions. The benzocrowns **B15**, **B18**, **DB18** and **DB24** were of commercial origin and were used without further purification. The quinocrowns **Q15**, **Q18** and benzocrown **B21** were prepared according to the published methods.[1b,21] The quinocrown **Q21**, diquinocrowns **DQ18** and **DQ24**, and quinobenzocrown **QB18** were synthesized by the modification of the literature methods[22] as follows.

22,25-Dioxo-2,5,8,11,14,17,20-heptaoxabicyclo[19.4.0]pentaicosa-1^{21},23^{24}-diene (quino-21-crown-7 Q21). Sodium hydroxide (9.6 g, 240 mmol) was added to a stirred solution of 1-benzyloxy-2,3-bis(2′-hydroxyethoxy)benzene **1** (9.1 g, 30 mmol) and tetraethylene glycol ditosylate (15.1 g, 30 mmol) in dry dioxane (500 ml), then the solution was heated at 80 °C for 24 h. The precipitate was filtered off and the filtrate was evaporated under reduced pressure to give a viscous residue. The residue was extracted with benzene to give 3-benzyloxybenzo-21-crown-7† **2** (13.2 g). Subsequently, a mixture of **2** (13.2 g) and Pd carbon (1 g) in dioxane (10 ml) was stirred under an atmosphere of hydrogen for 3 days. The catalyst was filtered off and the solvent was evaporated under reduced pressure to give 3-hydroxybenzo-21-crown-7 **3** (11.1 g) as an oil. Fremy's salt (3.8 g, 14 mmol) was added to a stirred suspension of **3** (0.86 g) in 5% aqueous sodium acetate (280 ml) containing a small amount of benzene (30 ml). After the mixture had been stirred at room temperature for 30 min, it was extracted with benzene (3 × 70 ml). The combined organic layers were dried ($MgSO_4$) and concentrated under reduced pressure. The residue was chromatographed on a silica gel with chloroform–THF (3:1 by volume) as an eluent to give **Q21** (409 mg, 46%) as a red oil. ^{1}H-NMR (270 MHz, $CDCl_3$) δ 3.66 (s, 8H), 3.68 (s, 8H), 3.81–3.85 (m, 4H), 4.45–4.49 (m, 4H) and 6.58 (s, 2H); IR (KBr) 2917, 1655, 1591, 1351, 1298, 1180, 1108, 951 and 845 cm^{-1}; MS (EI) *m*/*z* 388 (M$^+$, 20%), 298 (18%), 194 (30%), 179 (15%), 166 (100%), 138 (82%), 117 (21%), 89 (36%), 82 (49%), 73 (60%), 45 (98%); Found: C, 56.11; H, 7.08. Calc. for $C_{18}H_{26}O_9$: C, 55.95; H, 6.78%.

10,13,23,26-Tetraoxo-2,5,8,15,18,21-hexaoxatricyclo-[20.4.0.4^{9,14}]hexaicosa-1^{22},9^{14},11^{12},24^{25}-tetraene (diquino-18-crown-6 DQ18). A solution of 3-benzyloxypyrocatechol **4** (2 g, 9.25 mmol), diethylene glycol ditosylate (3.83 g, 9.25 mmol) and sodium hydroxide (2.96 g, 74 mmol) in dry dioxane (200 ml) was stirred for 24 h at 80 °C. The precipitate was filtered off and the filtrate was evaporated under reduced pressure to give a viscous residue. The residue was extracted with benzene to give 3,3′-dibenzyloxydibenzo-18-crown-6 **5** (2.72 g) as a brown oil. Subsequently, a mixture of **5** (2.72 g) and Pd carbon (0.5 g) in dioxane (3 ml) was stirred under an atmosphere of hydrogen for 3 days. The catalyst was filtered off and the solvent was evaporated under reduced pressure to give 3,3′-dihydroxydibenzo-18-crown-6 **6** (1.4 g) as an oil. Fremy's salt (3.8 g, 14 mmol) was added to a stirred suspension of **6** (0.88 g) in 5% aqueous sodium acetate (280 ml) containing a small amount of benzene (30 ml). After the mixture had been stirred at room temperature for 30 min, it was extracted with benzene (3 × 70 ml). The combined organic layers were dried ($MgSO_4$) and concentrated under reduced pressure. The residue was recrystallized from chloroform–hexane to give **DQ18** (0.23 g, overall yield 33%) as orange needles, mp 197–198 °C. ^{1}H-NMR (270 MHz, $CDCl_3$) δ 3.82–3.79 (m, 8H), 4.54–4.51 (m, 8H) and 6.59 (s, 4H); IR (KBr) 2901, 1654, 1591, 1474, 1379, 1331, 1295, 1205, 1177, 1140, 1080, 1034, 843, and 677 cm^{-1}; MS (EI) *m*/*z* 420 (M$^+$, 48%), 194 (100%), 179 (25%), 166 (70%), 138 (45%); Found: C, 57.35; H, 4.63. Calc. for $C_{20}H_{20}O_{10}$: C, 57.15; H, 4.80%.

13,16,29,32-Tetraoxo-2,5,8,11,18,21,24,27-octaoxatricyclo-[26.4.0.4.^{12,17}]dotriaconta-1^{28},12^{17},14^{15},30^{31}-tetraene (diquino-24-crown-8 DQ24). A solution of 3-benzyloxypyrocatecol **3** (5.1 g, 23.6 mmol), triethylene glycol ditosylate (10.8 g, 23.6 mmol) and sodium hydroxide (7.6 g, 189 mmol) in dry dioxane (500 ml) was stirred for 24 h at 80 °C. The precipitate was filtered off and the filtrate was evaporated under reduced pressure to give a viscous residue. The residue was extracted with benzene to give 3,3′-dibenzyloxydibenzo-24-crown-8 **7** (7.56 g) as a brown oil. Subsequently, a mixture of **7** (7.56 g) and Pd carbon (1 g) in dioxane (10 ml) was stirred under an atmosphere of hydrogen for 3 days. The catalyst was filtered off and the solvent evaporated under the reduced pressure to give 3,3′-dihydroxydibenzo-24-crown-8 **8** (4.2 g) as an oil. Fremy's salt (3.8 g, 14 mmol) was added to a stirred suspension of **8** (0.77 g) in 5% aqueous sodium acetate (280 ml) containing a small amount of benzene (30 ml). After the mixture had been stirred at room temperature for 30 min, it was extracted with benzene (3 × 70 ml). The combined organic layers were dried ($MgSO_4$) and concentrated under reduced pressure. The residue was chromatographed on a silica gel with chloroform as an eluent to give **DQ24** (0.32 g, overall yield 29%). Recrystallization from hexane–benzene gave crystalline **DQ24** as orange needles; mp 115–116 °C. ^{1}H-NMR (270 MHz, $CDCl_3$) δ 3.68 (s, 8H), 3.76–3.79 (m, 8H), 4.45–4.48 (m, 8H) and 6.58 (s, 4H); IR (KBr) 2873, 1677, 1654, 1587, 1560, 1286, 1201, 1165, 1075 and 845 cm^{-1}; MS (EI) *m*/*z* 508 (M$^+$, 6%), 420 (10.2%), 194 (55.96%), 167 (100%), 138 (29.7%) and 73 (23%); Found: C, 56.77; H, 5.77. Calc. for $C_{24}H_{28}O_{12}$: C, 56.69; H, 5.55%.

23,26-Dioxo-2,5,8,15,18,21-hexaoxatricyclo[20.4.0.4^{9,14}]-hexaicosa-1^{22},9^{14},10^{11},12^{13},24^{25}-pentaene (quinobenzo-18-crown-6 QB18). Sodium hydroxide (2.7 g, 67.5 mmol) was added to a stirred solution of 1-benzyloxy-2,3-bis(2′-hydroxyethoxy)benzene **1** (2.56 g, 8.42 mmol) and 2,3-bis(2′-tosyloxyethoxy)-benzene (4.26 g, 8.42 mmol) in dry dioxane (300 ml), then the solution was heated at 80 °C for 24 h. The precipitate was filtered off and the filtrate was evaporated under reduced pressure to give a viscous residue. The residue was extracted

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† The numbering of the benzyloxy group refers to its position on the benzene ring, and not to the overall numbering of the compound. This also applies similarly for compounds **1**, **3**, **5**, **6**, **7**, **8** and **10** in the rest of the Experimental.

with benzene to give 3′-benzyloxydibenzo-18-crown-6 **1** (3.74 g). Subsequently, a mixture of **1** (3.74 g) and Pd carbon (0.5 g) in dioxane (5 ml) was stirred under an atmosphere of hydrogen for 3 days. The catalyst was filtered off and the solvent was evaporated under reduced pressure to give 3′-hydroxydibenzo-18-crown-6 **10** (3 g) as an oil. Fremy's salt (3.8 g, 14 mmol) was added to a stirred suspension of **10** (0.72 g) in 5% aqueous sodium acetate (280 ml) containing a small amount of THF (30 ml). After the mixture had been stirred at room temperature for 30 min, it was extracted with benzene (3×50 ml). The combined organic layers were dried ($MgSO_4$) and concentrated under reduced pressure. The residue was chromatographed on a silica gel with chloroform as an eluent to give **QB18** (320 mg, 43%) as orange needles; mp 111–112 °C; ^{1}H-NMR (270 MHz, $CDCl_3$) δ 3.89–3.96 (m, 8H), 4.15–4.18 (m, 4H), 4.52–4.55 (m, 4H), and 6.54 (s, 2H); IR (KBr) 3064, 2926, 1672, 1655, 1588, 1508, 1454, 1329, 1280, 1260, 1184, 1133, 1079, 932 and 843 cm^{-1}; MS (EI) m/z 390 (M^+, 100%), 194 (19%), 180 (12%), 168 (14%), 167 (35%), 138 (82%), 136 (85%), 80 (11%); Found: C, 61.72; H, 5.66. Calc. for $C_{20}H_{22}O_8$: C, 61.53; H, 5.68%.

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