abstraction from N or O, they react with diphenylketyl more rapidly than the bulky resonance-stabilized ketyl radicals dimerize, Table II. C-Centered radicals formed from the *N,N,O*-trimethyl compound, and possibly in part from the others, are less stabilized and bulky than the ketyl, and would also increase rates of removal of ketyl.

Although the N- and O-centered radicals react very rapidly with ketyl radicals, they may not react rapidly alone. Nitroxide radicals from *N,N*-dialkylhydroxylamines may appear stable, in equilibrium with their dimers,[28] or they may disproportionate by slow transfer of H from α-C with rate constants $\sim 10^3$ M^{-1} s^{-1}.[6] Mono-*N*-alkylnitroxide radicals disproportionate more rapidly, with transfer of H from N and rate constants $>10^6$ M^{-1} s^{-1}.[7] *O,N*-Dialkyl- and *O*-monoalkyl N-centered radicals disappear more rapidly, apparently by initial dimerization, with rate constants $\sim 10^8$ M^{-1} s^{-1},[29] similar to that for diphenylketyl dimerization. In this study, reactions of the hydroxylamine-derived radicals with ketyl radical dominate over these self-destruction processes.

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Registry No. Benzophenone, 119-61-9; *O*-methylhydroxylamine, 67-62-9; *N,O*-dimethylhydroxylamine, 1117-97-1; *N,N*-diethylhydroxylamine, 3710-84-7; *N,N,O*-trimethylhydroxylamine, 5669-39-6; benzophenone ketyl radical, 16592-08-8.

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Molecular Recognition of Polar Neutral Molecules by Metallomacrocycles: Synthesis, ^{1}H NMR Spectroscopy, X-ray Structure, Electrochemistry, and Ab Initio Calculations

Arie R. van Doorn,[†] Robert Schaafstra,[†] Martinus Bos,[‡] Sybolt Harkema,[§] Johan van Eerden,[§] Willem Verboom,[†] and David N. Reinhoudt*[,†]

Laboratories of Organic Chemistry, Chemical Analysis, and Chemical Physics, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

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*Metallo*macrocycles **5** possessing an immobilized Lewis acidic uranyl group were synthesized by reaction of aldehydes **4** with *cis*-1,2-cyclohexanediamine in the presence of Ba^{2+} as a template cation and subsequent transmetallation with UO_2^{2+}. These metallomacrocycles are soluble in organic solvents and the complexation with neutral molecules was investigated by polarography, ^{1}H NMR spectroscopy, solid–liquid and liquid–liquid extraction experiments, X-ray structure determinations, and ab initio calculations. Several solid complexes (**6**) of metallomacrocycles **5b–d** with polar neutral molecules (formamide, acetamide, *N*-methylurea, hydroxyurea, urea, and DMSO) were isolated; a ring size selective complexation is observed. Polarography demonstrated a ring size affinity with the following stability order for the complexes in CH_3CN: urea > *N*-methylurea > acetamide ≈ formamide > acetone ≈ 0. The stability constants of the **6b**·urea and **6c**·urea complexes in $CDCl_3$ are according to ^{1}H NMR spectroscopy at least 10^8 M^{-1}; the highest number ever achieved by a complex consisting of a neutral *mono*metalloreceptor and a neutral molecule. The high stabilities were confirmed by solid–liquid and liquid–liquid extraction experiments. The crystal structures of the **6b**·urea and **6d**·urea complexes reveal that urea is encapsulated in the cavity and that the complexes are stabilized by coordination of the carbonyl oxygen of urea to the immobilized uranyl cation, multiple H-bond formation, and electrostatic interactions between urea nitrogens and ether oxygens. Ab initio calculations suggest that charge transfer determines the coordination between the uranyl cation and urea. The optimal coordination angle (C=O···M^{2+}) is approximately 130°, for both in-plane and perpendicular coordination.

Introduction

In supramolecular chemistry one of the major objectives is the selective complexation of *neutral guests*. The first generation of receptors for neutral molecules were relative simple and have only a moderate preorganization and complementarity between host and guest. The recognition of these receptors is based on H-bond formation of the acidic protons of the guest and the Lewis basic sites (e.g. crown ether oxygens) of the host.[1]

The structure of the second generation receptors is more complex. In the design of this new generation stereoelectronic and size complementarity play an important role. Both π–π stacking and H-bond formation contribute to the stability of these complexes.[2] For achievement higher

[†] Laboratory of Organic Chemistry.
[‡] Laboratory of Chemical Analysis.
[§] Laboratory of Chemical Physics.

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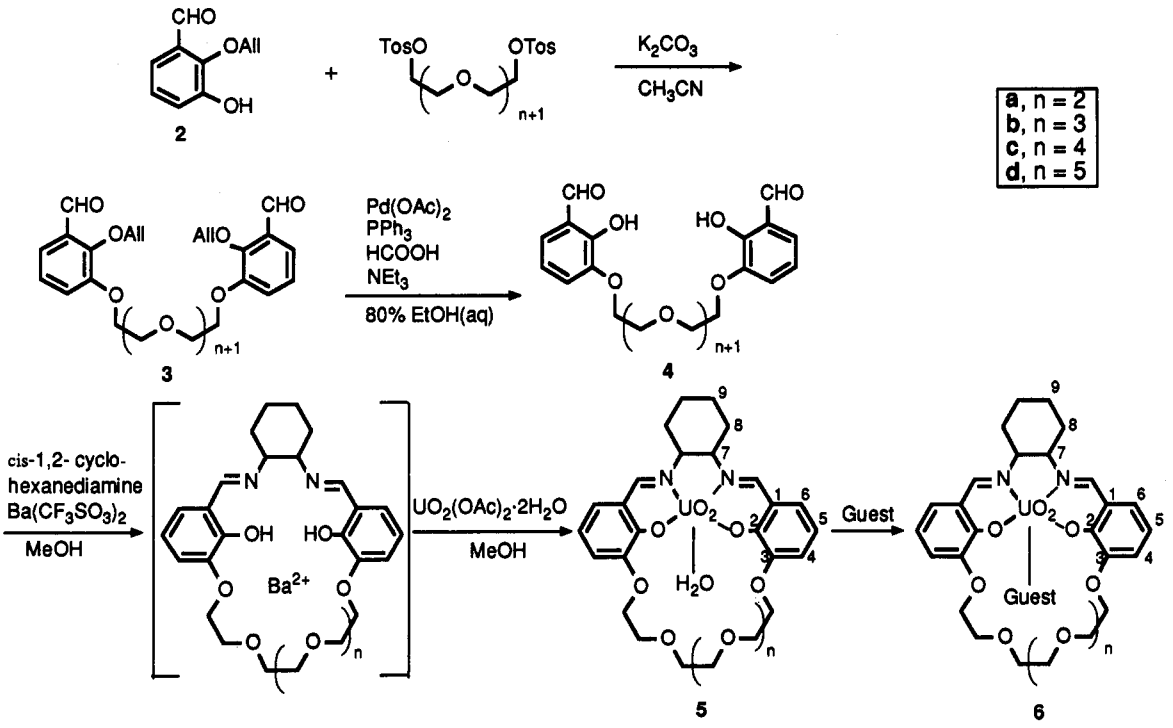
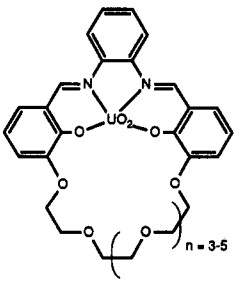
Scheme I



stabilities of the complexes, a third generation was invented with one or more acidic groups buried in the cavity of the macrocycle or the cleft.[2e,3] The drawback of Brönsted acidic groups is a limited pH range. In order to overcome these problems, we have developed a fourth generation in which an immobilized Lewis acidic group instead of a proton is used as an electrophilic center.[4]

From our previous work it is known that the Lewis acidic uranyl cation complexed in a salophene unit prefers a pentagonal-bipyramidal coordination, with the two oxygens at the apical positions and with both the four-coordinating sites of the salophene moiety and a *neutral molecule* in the equatorial positions.[4a-c] The salen and salophene moieties are known to form very stable complexes with transition-metal ions.[5,6] We have found that incorporation of an immobilized uranyl cation in a crown ether is a fruitful approach for the complexation of neutral polar molecules like urea (derivatives), acetamide, DMSO, and formamide.[4b] Unfortunately the solubility of metallomacrocycles 1 was too low to study the complexation in solution systematically (Chart I).

Chart I



1

In this paper the synthesis of metallomacrocycles that are soluble in organic solvents is described. The complexation of polar neutral molecules has been studied by ^1H NMR spectroscopy, X-ray crystallography, polarography, cyclic voltammetry, coulometry, and ab initio calculations. The complexation of urea by this type of compounds will be compared with that of other hosts.[2a,4a,b]

Results and Discussion

Synthesis. The synthesis of the metallomacrocycles is depicted in Scheme I. Dialdehydes 3 were prepared by reaction of 3-hydroxy-2-(2-propenoxy)benzaldehyde (2) and the appropriate ditosylate.[4b] The deallylation of 3 is possible with Pd/C but appeared to be much faster using $Pd(OAc)_2$, PPh_3, and an equimolar mixture of HCOOH and $N(Et)_3$;[7] dialdehydes 4 were obtained in 80–85% yield.

In order to improve the solubility of the metallomacrocycle 1, macrocyclization was achieved with *cis*-1,2-cyclohexanediamine. We have chosen the cis isomer be-

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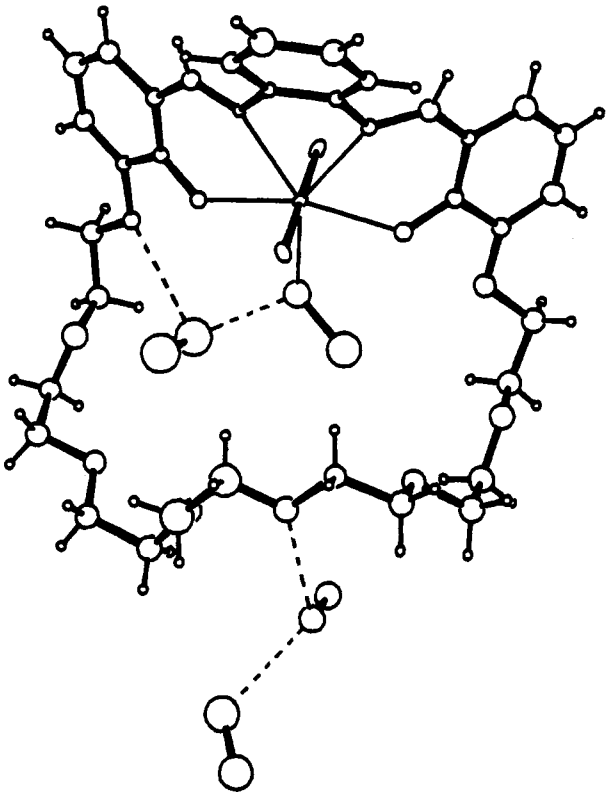

Figure 1. View of the X-ray structure of the 1(n=5)·MeOH complex.

cause in the chair conformer of the cyclohexyl moiety one nitrogen atom is located in the equatorial and one in the axial position. According to a CPK model, the nitrogens in these positions give after cyclization the desired cavity (vide infra) for immobilization of the uranyl cation.

Macrocyclization of dialdehydes **4** and *cis*-1,2-cyclohexanediamine was carried out by slow addition of both a solution of diamine and a solution of aldehyde in MeOH to a refluxing solution of $Ba(CF_3SO_3)_2$[8] in MeOH. The presence of the Ba^{2+} ion as a template is essential for macrocyclization. Addition of $UO_2(OAc)_2 \cdot 2H_2O$ and subsequent removal of the template ion with aqueous Na_2SO_4 afforded the metallomacrocyclic Schiff bases **5**·H_2O in 36–50% yield. Mixtures of complexes of **5** with water and methanol in the fifth position were obtained when during the workup the organic layer was not washed thoroughly with water.

For the less soluble metallomacrocycle **1** (n = 5) such a MeOH complex was isolated (Figure 1). Crystals suitable for X-ray analysis were grown by slow evaporation of MeOH. The cavity of this receptor is filled by two methanol molecules. One methanol molecule is coordinated via oxygen to the uranyl and the second methanol is H bonded to the coordinated methanol and an oxygen of the polyether ring. This structure reveals that in compounds like **1** and **5** there is a vacant coordination site at the uranyl moiety that is situated in the macrocyclic cavity. Details of the structure are given in the Experimental Section.

The ^1H NMR spectra of compounds **5** exhibit signals at 9.27 ppm (N=CH) and in the IR spectra absorptions are present at 1616–1614 cm^{-1}, indicating the imine bond formation. Absorptions at 900–896 cm^{-1} correspond to the asymmetric oxygen–uranium vibrations.[9] The electron impact mass spectra show intense M^+ peaks, proving tight complexation of the uranyl cation. The elemental analyses are in agreement with the proposed structures. Karl Fisher titrations proved the presence of water, most probably in the cavity of the macrocycle.

(8) Barium triflate was prepared by reaction of trifluoromethanesulfonic acid with barium hydroxide in MeOH. Evaporation to dryness gave the product as white crystals.

Table I. Crystalline Complexes[a]

guest	host 5a	5b	5c	5d
acetone	*b*	*b*	*b*	*b*
formamide	*b*	*b*	1:1	1:1
acetamide	*b*	*b*	1:1	1:1
N-methylurea	*b*	*b*	1:1	1:1
hydroxyurea	*b*	1:1	1:1	1:1
urea	*b*	1:1	1:1	1:1
DMSO	*b*	1:1	1:1	1:1

[a] Stoichiometric ratio metallomacrocycle:guest. [b] No complex isolated.

The conformation of the cyclohexyl moiety of the metallomacrocycle **5b**, which is assumed to be representative for the metallomacrocycles **5**, was studied by COSY and phase-sensitive NOESY[10] 2D NMR techniques in $CDCl_3$ at room temperature. Details are given in the Experimental Section.

The assignment of the cyclohexyl signals was made on the basis of correlations in the 2D COSY spectrum. These correlations show that the signals at 4.7–4.6, 2.6–2.5, 2.0–1.9, and 1.9–1.6 ppm are from the protons H-7,[11] H-8_{eq}, H-8_{ax},[12] and H-9, respectively. The signals of H-7 and H-9 protons are not separated in an axial and equatorial signal.

The correlations in the 2D NOESY spectrum are consistent with a chair conformation;[13] the imine nitrogens are nearly in plane with the phenolate oxygens and uranium atom. In the solid state a nearly identical conformer has been found (vide infra).

Complexation. Several aspects of the complexation properties of the metallomacrocycles **5** with polar neutral molecules (acetamide, formamide, hydroxyurea, *N*-methylurea, urea, and DMSO) were studied. Two of the isolated urea complexes were investigated by X-ray analysis and ab initio calculations to clarify complexation and coordination aspects. In solution the urea complexes were studied by ^1H NMR spectroscopy and liquid–liquid and solid–liquid extraction experiments. Other complexes were studied in CH_3CN by polarography.

Solid Complexes. Precipitation of the complexes from a solution of metallomacrocycle **5** and an excess of neutral guest in MeOH and/or $CHCl_3$ was achieved by using three different methods, viz. (i) cooling down the mixture to −30 °C, (ii) partial evaporation of the solvent, and (iii) diffusion of petroleum ether (bp 40–60 °C) into the solvent system. The elemental analyses proved the formation of 1:1 complexes.

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(10) (a) No positive peaks are observed; this means that no conformational mobility is suggested. (b) Bodenhaus, G.; Kogler, H.; Ernst, R. R. *J. Magn. Reson.* **1984**, *58*, 1984.

(11) In similar type compounds with other transition metal ions cocomplexed in the salen moiety the corresponding signal is found at 3.49–3.25 ppm; see ref 4b.

(12) (a) eq = equatorial; ax = axial. (b) Normally the equatorial proton is found about 0.5 ppm downfield from the axial proton, see: Günther, H. *NMR-Spektroskopie*; George Thieme Verlag: Stuttgart, 1983; p 75.

(13) Theoretically another chair conformation is possible with the imine "substituents" in different positions, but this seems very unlikely because in this interpretation the nitrogen lone pairs are then pointing away from the uranyl cation. The differences in interpretation are correlation between H_7–H_8 and H_{imine}–H'_7 instead of H_7–H_8 and H_{imine}–H'_9.

In general the predictions based on CPK models and the experimental results were in good agreement. All complexes with acetamide, *N*-methylurea, hydroxyurea, urea, and DMSO that show good fits have been isolated (Table I).

Only the complex of **5b** with formamide was not isolated but in solution complexation was demonstrated (vide infra). The precipitate we obtained contains less than 1 equiv of formamide. Acetone has a good fit in the CPK models with **5c** (n = 4) and **5d** (n = 5) but nonetheless no complexes were isolated. The melting points of the complexes **6** are higher than those of the corresponding free ligands **5**, probably reflecting the increased rigidity upon complexation. In the positive ion fast atom bombardment mass spectra the **6b–d**·hydroxyurea and **6b–c**·urea complexes reveal signals of both the 1:1 complex and the metallomacrocycle; the other complexes exhibit only a signal for the molecular ion peak of the metallomacrocycle.

In the IR spectra (in KBr) characteristic absorptions are present for the guest C=O or S=O stretching vibrations.[4b] Upon complexation these vibrations[14] shift to a lower wavenumber ($\Delta\nu$ = 4–59 cm^{-1}), which is in agreement with coordination of the oxygen to the immobilized uranyl cation. The C=O stretching frequency of hydroxyurea shifts upon complexation to a higher wavenumber ($\Delta\nu$ = 1–23 cm^{-1}). It is possible that the oxygen of the hydroxyl group coordinates to the uranyl, resulting in a higher wavenumber of the C=O stretching frequency. Unfortunately no crystals suitable for X-ray analysis could be obtained of the hydroxyurea complexes.

The ^{1}H NMR spectra of all the complexes **6** differ from those of the corresponding free ligands **5**. The most significant changes (shift and pattern of the signals) of the host were found for the polyether moiety signals, indicating the presence of the neutral molecules in the cavity. Hydroxyurea, insoluble in $CDCl_3$, exhibits in the complex signals between 9.9 and 7.4 ppm. In the spectra of the other complexes, only very broad signals of the guest are present, which are sometimes hidden under the polyethylene glycol signals. For complexed urea one or two broad singlets are found at 7.7–6.5 ppm. The NH signal(s) of urea is(are) found more downfield than in Bell's urea complex (6.3–6.7 ppm),[2a] suggesting a stronger H bond.

The (isolated) urea complexes **6b**·urea, **6c**·urea, and **6d**·urea, were studied in more detail with ^{1}H NMR spectroscopy in $CDCl_3$ at room temperature to get information on the stability of the complexes. The complexation–decomplexation of all these complexes is slow on the 250-MHz NMR time scale. The free ligand and the complex can be easily distinguished; representative examples are given in Figure 2. Even in 0.4 mM concentrations no dissociation could be observed and this means that ≥95% of the urea is still complexed at this concentration, corresponding to an association constant of ≥1.0 × 10^6 M^{-1}.

In a second set of experiments the relative stabilities of the complexes according to equilibrium 1 were measured.

$$H_1 + H_2\cdot\text{urea} \rightleftharpoons H_1\cdot\text{urea} + H_2$$

$$K_{rel} = [H_1\cdot\text{urea}][H_2]/[H_1][H_2\cdot\text{urea}] \qquad (1)$$

Since from the dilution experiments it follows that even at a concentration of 0.4 mM no detectable amount of free urea is present, it means that if a free ligand H_1 and a complex H_2·urea are mixed in a 1:1 ratio, after equilibration[15] urea is complexed (either) to ligand H_1 and/or to ligand H_2. The **6c**·urea complex exhibits an isolated OCH_2 signal at 4.9–4.8 ppm, which is of key importance and the relative stability is calculated with equation [1]. The results of the competition experiments are given in Table II and they show that the stabilities of the **6b–d**·urea complexes are much higher than that of the best urea receptor (**7**) (Chart II) previously reported by Bell.[2a] By combining the results of the dilution and competition experiments we were able to calculate new limits for the association constants of the **6a–d**·urea complexes: **6a**·urea ≤ 1 × 10^2, **6b**·urea ≥ 1.0 × 10^8, **6c**·urea ≥ 2.5 × 10^8, **6d**·urea ≥ 1.0 × 10^6 M^{-1}. Ring size selectivity is very clear and reaches an optimum for **6c**·urea. Based on CPK models and solid state data (vide infra), we would predict the highest stability for the **6b**·urea complex because this ligand has the optimal cavity. The present results might be explained by a more favorable balance of the enthalpy and entropy of complexation of **6c**·urea.[16] In $CDCl_3$ the complexes are up to ≥5000 times more stable then the **7**·urea complex.[17] This must be due to the immobilized Lewis acidic uranyl cation, because our receptors are less preorganized than **7** and according to Taft's definition[19] the ether oxygens form weaker hydrogen bonds than do

Table II. Relative Association Constants in $CDCl_3$ at 298 K

complexes[a,b]	K_{rel}[c]
7·urea/**6a**·urea	≥100
6b·urea/**7**·urea	≥100
6c·urea/**7**·urea	≥100
6d·urea/**7**·urea	20
6c·urea/**6d**·urea	≥100
6c·urea/**6b**·urea	2.5

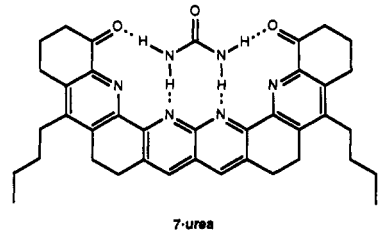
[a] Measured in the concentration range 0.4–4.0 mM. [b] K_{ass} of **7**·urea ≥ 4.0 × 10^4 M^{-1} (ref 2a). [c] Relative association constant.

Table III. Extraction of Urea in Water by a 5 mM Solution of Metallomacrocycles 5 in $CDCl_3$

	urea/**5**[b]		
host	1 M[a]	0.1 M[a]	0.05 M[a]
5a	<0.05	<0.05	<0.05
5b	>0.95	>0.95	0.75
5c	>0.95	>0.95	>0.95
5d	>0.95	0.50	0.10

[a] Urea concentration in the water layer. [b] Ratio in the $CHCl_3$ layer.

Chart II



7·urea

(14) The C=O stretching vibrations of urea, hydroxyurea, *N*-methylurea, acetamide, and formamide are found at 1678, 1641, 1654, 1668, and 1680 cm^{-1}, respectively. For the S=O stretching frequency of DMSO 1056 cm^{-1} was measured.

(15) Spectra were recorded after at least a 2-h equilibration time; control spectra recorded after 24 h gave the same ratio.

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(17) Bell[2a] has reported a minimal association constant of 4.0 × 10^4 M^{-1} for the urea complex in dry chloroform. From our results we concluded it must be at least 5.0 × 10^4 M^{-1} (**6d**·urea ≥ 1.0 × 10^6 M^{-1}; **6d**·urea/**7**·urea = 20) in wet chloroform. In addition, Wilcox et al.[18] have reported a small influence of the water concentration in $CDCl_3$ on the association constant.

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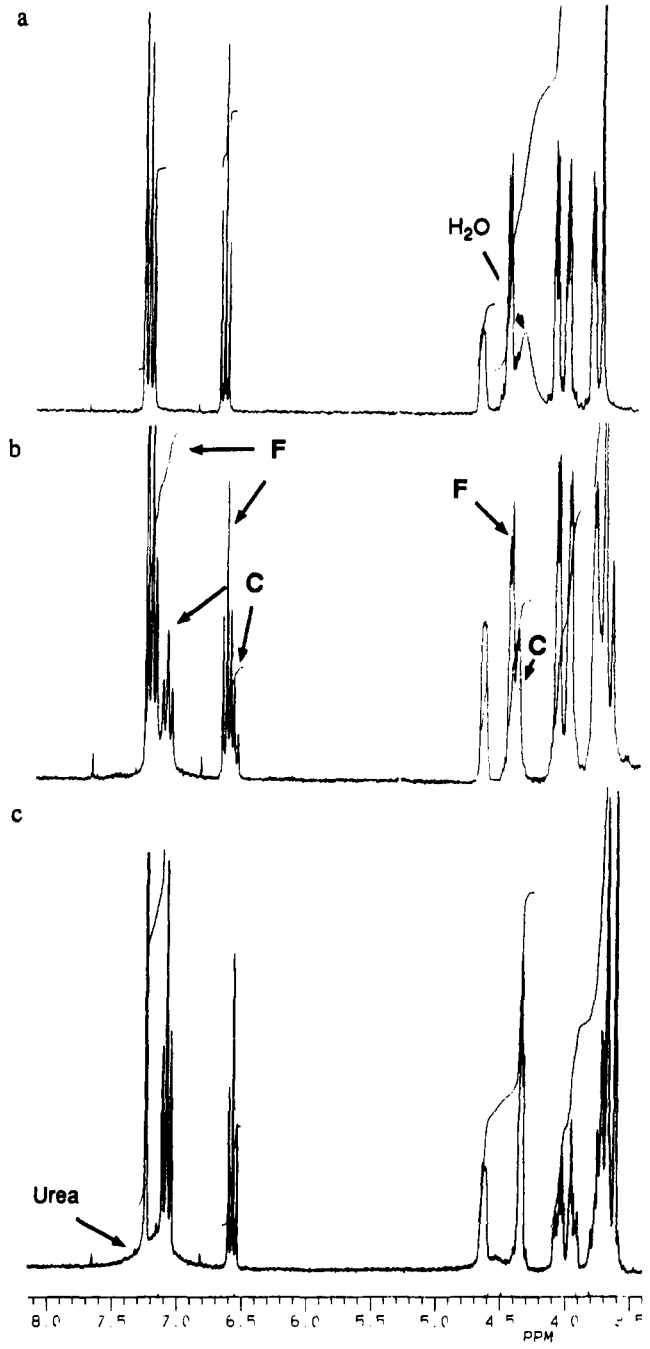


Figure 2. ^1H NMR spectrum of (a) free ligand **5b**·H_2O, (b) a 2:1 mixture of free ligand (= F) **5b** and complex (= C) **6b**·urea, (c) complex **6b**·urea.

the pyridine nitrogens. To the best of our knowledge the **6b–d**·urea complexes are the most stable complexes of a neutral *mono*metallo host and a neutral guest ever reported in supramolecular chemistry.[20]

Solid–Liquid Extraction Experiments were performed with 4×10^{-3} M of **5** in $CHCl_3$. No complexation of urea was observed, as expected, for the metallomacrocycle **5a**. For the metallomacrocycles **5b–d** more than 0.95 equiv of urea was found after equilibration.

The results of the *liquid–liquid extraction experiments* in $CHCl_3$ at three different urea concentrations are given in Table III. The same stability order[21] is found for the urea complexes as in the ^1H NMR dilution and competition experiments.

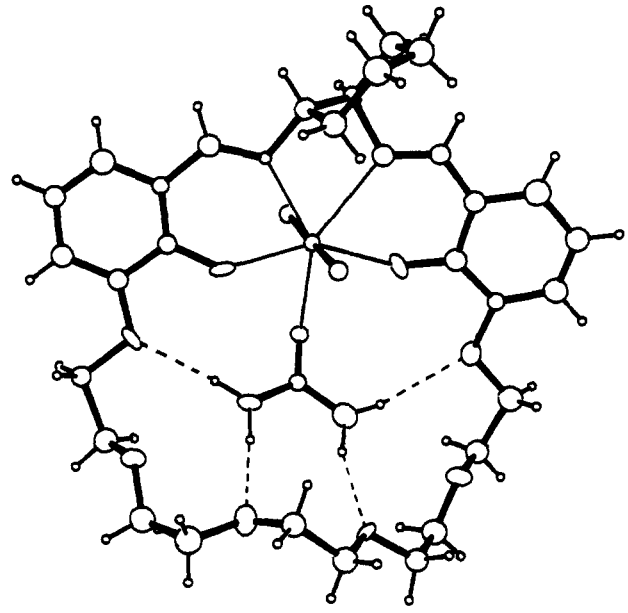


Figure 3. View of the X-ray structure of the **6b**·urea complex.

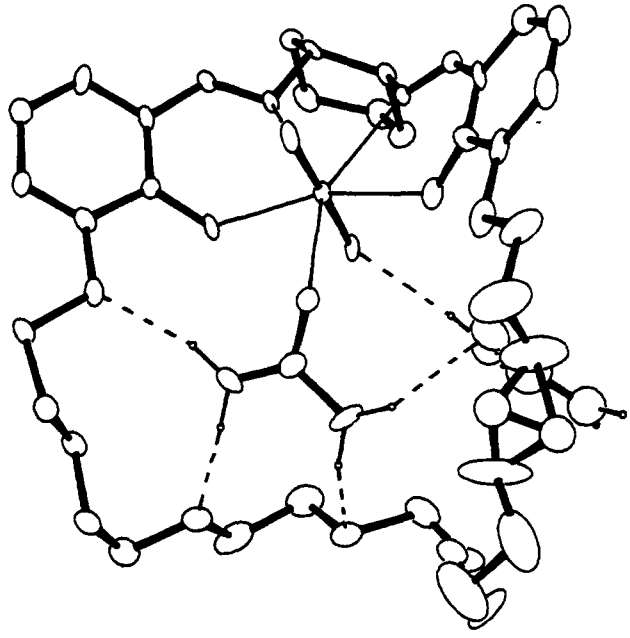


Figure 4. View of the X-ray structure of the **6d**·urea complex.

Table IV. Selected Distances (Å) and Angles (deg)

compd	**6b**·urea	**6d**·urea
$U-O_{apical}$	1.75	1.72–1.74
$U-O_{phenolate}$	2.25–2.29	2.31–2.38
$U-N_{imine}$	2.52–2.58	2.58–2.60
$U-O_{urea}$	2.36	2.36
$N_{urea}-O_{ether}$	3.02–3.04	3.09–3.15
H_{bond} (H···O)[a]	1.99–2.50	2.07–2.31
angle (O···H–N)	158–177	146–174
angle (U···O=C)	127	128

[a] Standard bond length of 0.95 Å for the hydrogens.

X-ray. The solid-state structures of the complexes **6b**·urea and **6d**·urea were determined by X-ray crystal-

(20) A receptor with three immobilized Zn^{2+} cations has been published, which forms the most stable complex in $CDCl_3$ (with 2,4,6-tri-4-pyridyl-*s*-triazine) ever reported with a K_{ass} of 10^9–10^{10} M^{-1}; Anderson, H. L.; Sanders, J. K. M. *J. Chem. Soc., Chem. Commun.* **1989**, 1714.

(21) Using a K_d of 1×10^{-4} for the distribution of urea between water and $CHCl_3$, which is measured colorimetrically by J. Lui (Dissertation, SUNY Stony Brook, NY, 1990, pp 52–53), the association constants of the urea complexes of **5a–d** *under extraction conditions* are $\leq 5 \times 10^2$, $\geq 6.0 \times 10^5$, $\geq 4.0 \times 10^6$, and $\geq 2.0 \times 10^4$, respectively.

lography. Details of the structure determinations, crystal data, and data collection parameters are given in the Experimental Section. ORTEP[22] views are shown in Figures 3 and 4. The coordination of uranium and the H bonds are depicted by bonds. In Table IV selected bond distances and angles are presented. Crystals of the urea complexes were grown by slow diffusion of petroleum ether (bp 40–60 °C) into a solution of urea complex in $CHCl_3$.

In both crystal structures the cyclohexyl moiety has a chair conformation. From the dihedral angles we concluded that the position of the imine "substituents" is very similar to the conformation found in solution (see also Chart IV, Experimental Section).

The five coordinating atoms (two imine nitrogens, two phenolate oxygens, and a urea oxygen) and uranium are found within 0.01 Å of their mean planes. The resulting bipyramidal-pentagonal coordination of the uranyl in the salen moiety is similar to the coordination found for the uranyl in the salophene moiety.[4a-c]

The Schiff base moiety deviates from planarity with angles between the aromatic rings of 7° and 77°, for **6b**·urea and **6d**·urea, respectively. From Figures 3 and 4 it is clear that the position of the aromatic rings with respect to the plane of coordinating atoms is quite different. In the **6b**·urea complex the phenyl rings are on the same side of the coordination plane while in the **6d**·urea complex the phenyl rings are on different sides, forming a half-open shell. The reason for this difference is not clear.

The main difference between the structures of the complexes is the position of urea in the cavity. In the **6d**·urea complex the fit of urea in the cavity is not perfect, because of the oversized cavity.[23] The complex is stabilized by three linear H bonds between urea hydrogens and ether oxygens of the metallomacrocycle, by coordination of the carbonyl oxygen of urea to the uranyl, and by two electrostatic attractions, viz., between a partially negatively charged polyether oxygen and a partially positively charged urea nitrogen. The fourth H bond (149°, 3.07 Å) of the encapsulated urea is to the carbonyl oxygen of a second urea molecule, which is situated outside the cavity. Interestingly, this second urea molecule has a linear H bond (171°, 3.27 Å) with one of the apical oxygens of the uranyl moiety. The existence of this type of H bond is also postulated to explain the polarographic results (vide infra). The part of the polyether ring that is not involved in the complexation is rather disordered; for optimal refinement one atom had to be placed in two positions, the other atoms have a large anisotropy in their thermal parameters.

In the **6b**·urea complex urea fits nearly perfectly in the cavity. The complex is stabilized by four linear H bonds to the ether oxygens, coordination at the uranyl, and two electrostatic attractions between two partially negatively charged polyether oxygens and the partially positively charged nitrogens of urea.

The presented crystal structures give a clear indication why the **6b**·urea complex in solution is more stable than the **6d**·urea complex. The good fit of the urea in the cavity, resulting in nearly optimal H bonds and electrostatic interactions, is in addition to coordination at the uranyl, one of the factors determining the stability of the complexes (vide infra).

In the **6d**·urea complex a normal in-plane coordination with an angle of 128° (C=O···UO_2^{2+}) is found. In the **6b**·urea complex an abnormal coordination mode is found with an angle of 127° perpendicular to the urea plane. From these results the question arises which coordination mode is preferred.

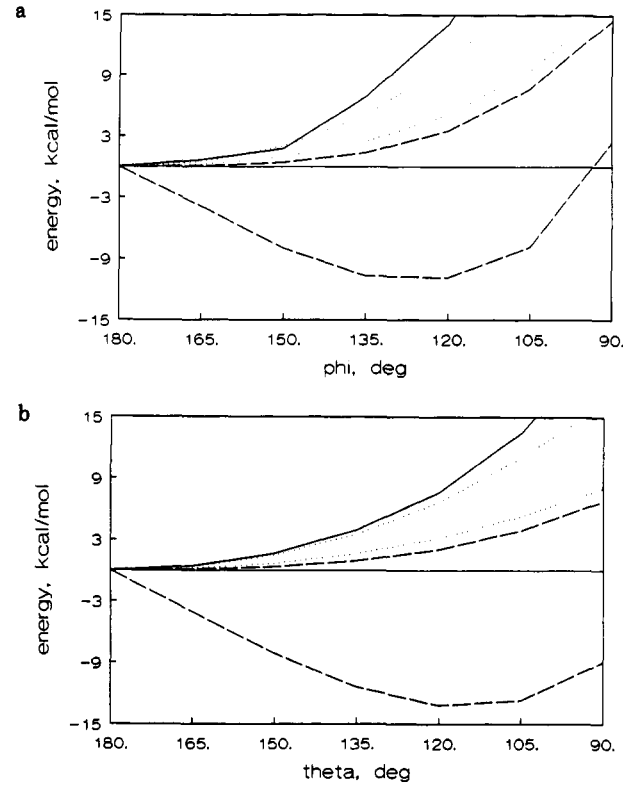


Figure 5. Total energy of the urea point-charge system, relative to linear coordination, as a function of the coordination angles (a) ϕ (planar) and (b) θ (perpendicular), for different point-charge models: without charge transfer (0.5 e and 1.0 e, ab initio, lower and upper dotted curve, respectively; 1.0 e, semiempirical, full line), with charge transfer (0.5 e and 1.0 e, ab initio, upper and lower dashed curve, respectively).

The preferences in coordination of urea by a metal cation were studied via calculations using ab initio and semiempirical methods. Because of the lack of parameters, a point charge is used to model the positively charged uranyl. As it is not clear how well an immobilized (uranyl) metal ion is modeled by a simple point charge, several point-charge models were used, with different values of the charge and with differences in the charge-transfer properties. The energies were calculated for urea coordinated at the carbonyl oxygen by a positive point charge at different values of the coordination angles ϕ and θ (C=O···+), where ϕ represents the angle in the plane of urea and θ the angle perpendicular to the plane of urea.

First a planar coordination was considered. A point charge of 1.0 e was used in a model allowing no charge transfer; the ab initio calculation (Figure 5a, upper dotted curve) showed a strong preference for linear coordination (ϕ = 180°). Coordination at the lone pair(s) (ϕ = 135°) was unfavorable by 5 kcal mol^{-1}. Semiemperical calculations with a *sparkle* point charge of 1.0 e showed the same trend (Figure 5a, full line), with a corresponding energy difference of 7 kcal mol^{-1}. Ab initio calculations with a point charge of 0.5 e without charge transfer (Figure 5a, lower dotted curve) gave a proportional result, with an energy difference of 2.5 kcal mol^{-1}. So all calculations using a point-charge model that allows no charge transfer showed a preference for linear coordination.

Experimental results such as the shift to longer wavelengths in IR frequency of the C=O vibration (vide supra),

(22) Johnson, C. K. *ORTEP*, Report ORNL-3794; Oak Ridge Laboratory: Oak Ridge, TN, 1965.

(23) In ref 4b the X-ray structure of the corresponding 1(n=5)·urea complex has been reported.

however, suggest charge transfer. Therefore a point-charge model allowing charge transfer was also used in ab initio calculations. With a value of the point charge of 0.5 e (Figure 5a, upper dashed curve) only a slight change was found compared with the previous result (0.5 e, without charge transfer). Mulliken population analysis indicated a small amount of charge transfer (–0.01 to –0.05 e) to the point charge. With a charge value of 1.0 e a different result was obtained (Figure 5a, lower dashed curve). The energy exhibits a minimum of 11 kcal mol^{-1} (relative to ϕ = 180°) in the range of 120–135°. This orientation of the minimum corresponds to the lone-pair direction observed in electron-density difference studies of urea[24] and the preference in orientation for metal–cation coordination with urea.[25] The charge transfer, according to Mulliken population analysis, was considerably larger, increasing from –0.12 to –0.48 e over the ϕ range from 180° to 90°. The large amount of charge transfer and the strong increase of the energy at ϕ = 90° is probably related to the proximity of a urea H atom.

Subsequently the perpendicular coordination was considered. The same point-charge models were employed, and similar results were obtained (Figure 5b) as with the planar coordination. Again the curve for the 1.0 e point charge with charge transfer exhibits a comparable minimum energy (13 kcal mol^{-1}) in the range of 120–135°. The increase of energy at θ = 90° is not as strong as for planar coordination because there is no proximity of a H atom.

The results suggest that charge transfer determines the observed coordination of the metal cation to urea at a ϕ or θ angle[26] of approximately 130°. As it is not clear what point-charge model, regarding to magnitude of the charge and degree of the charge transfer, gives the best description of the immobilized uranyl cation, these can only be qualitative conclusions for the coordination of urea to a uranyl cation. But nevertheless the model and the presented X-ray structures show excellent agreement with respect to the coordination angles.

The results of the calculations suggest that a perpendicular coordination as found in **6b**·urea can be used to form complexes that are as stable as planar coordination complexes. An advantage of the perpendicular coordination mode is that receptors can be symmetrical, which makes them synthetically more accessible.

Electrochemistry. Polarography[27] has been used in supramolecular chemistry to measure the stability constants of host–guest complexes. Hosts are (macrocyclic) ligands and guests can be cations[28] or neutral molecules.[4c]

One- and two-electron reductions have been reported for the uranyl cation.[27] Coulometry at a constant potential of –1300 mV in CH_3CN with $Et_4N^+ClO_4^-$ as a supporting electrolyte reveals that the first reduction step of **5** is a one-electron transfer. Cyclic voltammetry in the same solvent system showed that the reduction of **5** is electrochemically reversible.

The reduction properties of **5a–d** were studied with sampled DC polarography in CH_3CN with $Et_4N^+ClO_4^-$ as the supporting electrolyte. The polarograms were recorded in the range of –800 mV and –1300 mV and were evaluated by Zollinger's program.[29] The results are presented in Table V. The reduction potentials of the compounds **5a–d** are nearly independent of the ring size.

Table V. Polarographic Data for the Reduction at a Dropping Mercury Electrode at 293 K in 0.1 M $Et_4N^+ClO_4^-$ in CH_3CN vs Ag/AgCl

compd	$E_{1/2}$ (mV)	I_l (nA)	slope (mV)	concn (mM)
5a	–1124	1.86	63	0.98
5b	–1123	1.66	66	0.98
5c	–1107	1.54	69	0.96
5d	–1110	1.31	72	0.97

Table VI. Association Constants (M^{-1}) in CH_3CN at 293 K

guest	host			
	5a	**5b**	**5c**	**5d**
acetone	<10	<10	<10	<10
formamide	<10[a]	170	81	<25
acetamide	<10[a]	<25	89	<25
N-methylurea	<10[a]	891	2137	16982
urea	<10[a]	$>10^{+5}$	10^{+5}	$>10^{+5}$

[a] Anodic shift; see text.

The polar *neutral* guests were added in a titration experiment because hosts **5a–d** are the reducible species; the polarographic data were evaluated by the computer program POLAG.[30,31] The results are presented in Table VI. Several conclusions can be drawn from the data presented in Table VI: (i) Ring-size selectivity is clearly demonstrated. As predicted (vide supra) the cavity of metallomacrocycle **5a** is too small to accommodate any of the neutral guests of Table VI. For the metallomacrocycles with larger rings (**5b–d**) the complexes with the best fit (according to CPK models) always have the highest stability. For instance, formamide has an optimal fit with **5b**, for the larger metallomacrocycles **5c** and **5d** a decreasing stability is measured. For *N*-methylurea just the opposite is observed. (ii) Acetone did not give complexes in CH_3CN at 293 K ($K_{ass.} \leq 10\ M^{-1}$) and this explains why solid complexes were not isolated (vide supra). (iii) From the anodic shift of the reduction potential of **5a** upon addition of urea we conclude that urea is complexed better in the reduced form of **5a** and that coordination is not at the fifth position of uranyl. At least two examples have been reported of a better complexation of a guest by a reduced host,[32] upon reduction the metal ions have larger radii and fit better in the cavity. In our case an explanation may be H-bond formation between the urea hydrogen and the apical uranyl oxygen; these oxygens should be more negative in the reduced state. In the solid-state structure of **6d**·urea such a H bond is present. For the other guests the anodic shifts are (nearly) absent and we do not expect it to interfere with normal complexation of the larger ring metallomacrocycles. (iv) The stability of the urea complexes **5b–d** is too high to be measured by polarography.[33] The concentration required to measure the stability of those complexes is lower than the limit of the polarographic method ($c \geq 2 \times 10^{-4}$ M).

Conclusions

A convenient route to the readily soluble metallomacrocycles **5** is described. The complexing properties of the cyclohexyl metallomacrocycles **5** are comparable with

(24) Lebioda, L. *Acta Crystallogr., Sect. B* **1980**, *36*, 271.
(25) (a) Scheringer, C.; Mullen, D.; Hellner, E.; Hase, H. L.; Schulte, K.-W.; Schweig, A. *Acta Crystallogr., Sect. B* **1978**, *34*, 2241. (b) Swaminathan, S.; Craven, B. M.; Spackman, M. A.; Stewart, R. F. *Acta Crystallogr., Sect. B* **1984**, *40*, 271.
(26) Similar results were obtained in the range between planar and perpendicular coordination; results are not shown.
(27) Heyrovski, J.; Kuta, J. *Grundlagen der Polarografie*; Schwabe, K., Ed.; Akademie-Verlag: Berlin, 1965.
(28) Izatt, R. M.; Bradshaw, J. S.; Nielsen, N. A.; Lamb, J. D.; Christensen, J. J. *Chem. Rev.* **1985**, *85*, 271.
(29) Zollinger, D. P.; Bos, M.; van Veen-Blaauw, A. M. W.; van der Linden, W. E. *Anal. Chim. Acta* **1985**, *167*, 89.
(30) Legett, D. J. *Talanta* **1980**, *27*, 787.
(31) A typical example of data-input is given in ref 4c.
(32) (a) Gansow, O. A.; Kauser, A. R.; Triplett, K. M.; Weaver, M. J.; Yee, E. L. *J. Am. Chem. Soc.* **1977**, *99*, 7087. (b) Massaux, J.; Desreux, J. F.; Delchambre, C.; Duyckaerts, G. *Inorg. Chem.* **1980**, *19*, 1893.
(33) Competition experiments with *N*-methylurea were not successful.

the salophene metallomacrocycles 1. However, due to the better solubility of 5 in organic solvents (e.g., toluene, $CHCl_3$, CH_2Cl_2, THF, CH_3CN), the complexation behavior could be studied in detail. Several complexes of **5b–d** with neutral molecules (formamide, acetamide, *N*-methylurea, hydroxyurea, urea, and DMSO) were isolated. Polarographic studies in CH_3CN reveal a ring-size selective affinity for *neutral polar organic molecules*. The following stability order in CH_3CN was found: urea > *N*-methylurea > formamide ≈ acetamide > acetone ≈ 0. The stabilities of the urea complexes are too high to be measured with polarography. By combining dilution and competition ^1H NMR experiments a lower limit for the association constant of 10^8 M^{-1} is calculated for the **6b**·urea and **6c**·urea complexes in $CDCl_3$ at 298 K. For the **6d**·urea complex a minimal association constant of 10^6 M^{-1} was calculated. The urea complexes are the most stable complexes reported between a neutral monometallic receptor and neutral guest. The results of the solid–liquid and liquid–liquid extraction experiments are in line with the results of the ^1H NMR experiments. According to X-ray analyses urea is encapsulated in the cavity. The **6b**·urea and **6d**·urea complexes are stabilized by coordination of the urea oxygen to the immobilized uranyl cation, multiple H-bond formation, and electrostatic interactions. Ab inito calculations showed for urea an optimal coordination angle of approximately 130°, which is in agreement with the angles found in the presented structures and with literature reports.

Experimental Section

General Methods. NMR spectra were recorded in $CDCl_3$ with TMS as internal standard. Assignments of the NMR spectra are according to the numbering in Scheme I. The assignment of cyclohexyl protons is not subdivided in H_x and H_x' (X = 7, 8, 9; see Charts III and IV) because these signals are not separated. Positive ion fast atom bombardment (FAB) mass spectra were obtained with *m*-nitrobenzyl alcohol as a matrix. Melting points were uncorrected. Petroleum ether and CH_2Cl_2 were distilled before use. Petroleum ether refers to the fraction with bp 40–60 °C, and DIP refers to diisopropyl ether. Other chemicals were of reagent grade and were used without purification. Column chromatography was performed with silica gel (Merck; 0.015–0.040 mm; 230–400 ASTM). All reactions were carried out in a static nitrogen atmosphere. Dropwise additions over a period of several hours were carried out with a perfusor. If not stated otherwise the organic layers were (after extraction from the water layer) dried over $MgSO_4$ and concentrated in vacuo. Karl Fischer titrations were performed by using the indirect method.[34] Compounds **1**, **2**, **3**, and **4a**[4b] and complex **7**·urea[2a,35] were synthesized according to literature procedures. Care should be taken when handling uranyl-containing compounds because of their toxicity and radioactivity.

General Procedure for the Synthesis of the Compounds 4b–d. A mixture of aldehyde **3** (3–8 mmol), $Pd(OAc)_2$ (2 mol %), PPh_3 (8 mol %), HCOOH (6 equiv), and $HNEt_3$ (6 equiv) was refluxed in 80% aqueous EtOH for 3 h. Most of the solvent was evaporated and the remaining mixture was acidified with 1 M HCl (50 mL) and was extracted with CH_2Cl_2 (3 × 50 mL). Pure aldehydes **4** were obtained after flash chromatography (CH_2Cl_2:MeOH 100:1) in a yield of 80–85%. ^1H NMR data are identical with previously reported data.[4b]

General Procedure for the Synthesis of Compounds 5. To a refluxing solution of $Ba(CF_3SO_3)_2$ (2–5 mmol) in MeOH (250 mL) were added separate solutions of aldehyde **4** (1 equiv) in MeOH (50 mL) and *cis*-1,2-cyclohexanediamine (1 equiv) in MeOH (50 mL). After 30 min, 1 equiv of $UO_2(OAc)_2 \cdot 2H_2O$ was added. Reflux was maintained another 30 min before the mixture was cooled to room temperature. The solvent was evaporated and the residue was dissolved in CH_2Cl_2 and was successively washed thoroughly with a saturated aqueous solution of Na_2SO_4 (3 × 100 mL), $NaHCO_3$ (1 × 100 mL), and brine (1 × 100 mL). Pure uranyl compound **5** was obtained by flash chromatography (eluent is indicated for the individual compounds) followed by precipitation from CH_2Cl_2 with petroleum ether.

Chart III

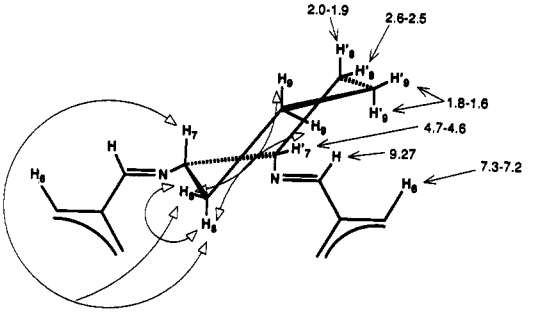
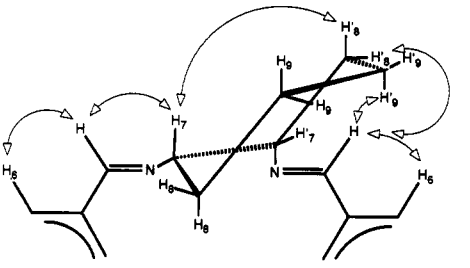


Chart IV



[*cis*-9,10,12,13,15,16,18,19,27a,28,29,30,31,31a-Tetradecahydro-3,7:21,25-dimetheno-8,11,14,17,20,1,27-benzopentaoxadiazacyclononacosine-32,33-diolato(2−)-N^1,N^{27},O^{32},O^{33}]dioxouranium·1.3H_2O·1.0CH_2Cl_2 (5a): eluent CH_2Cl_2:MeOH 25:1; yield 36%; mp 105–108 °C (CH_2Cl_2/petroleum ether); ^1H NMR δ 9.27 (s, 2 H, CH=N), 7.4–7.2 (m, 4 H, H-4, H-6), 6.65 (dd, *J* = 7.7 Hz, 2 H, H-5), 5.22 (s, 2 H, 1.0 CH_2Cl_2), 4.7–4.6 (m, 2 H, H-7), 4.5–4.4 (m, 4 H, OCH_2), 4.1–4.0 (m, 4 H, OCH_2), 4.0–3.9 (m, 4 H, OCH_2), 3.8–3.7 (m, 4 H, OCH_2), 2.6–2.4 (m, 2 H, H-8_{eq}), 2.0–1.8 (m, 2 H, H-8_{ax}), 1.9–1.6 (m, 4 H, H-9); ^{13}C NMR δ 167.8 (d, CH=N), 161.6 (s, C-2), 149.9 (s, C-3), 128.8 (d, C-6), 124.9 (s, C-1), 123.7 (d, C-5), 116.6 (d, C-4), 71.5 (d, C-7), 70.9, 70.8, 70.7, 70.2 (t, OCH_2), 27.9 (t, C-8), 21.8 (t, C-9); IR (KBr) 1616 (C=N), 896 (O–U–O) cm^{-1}; mass spectrum (EI), *m*/*z* 780.280 (M^+, calcd 780.277). Anal. Calcd for $C_{28}H_{34}N_2O_9U \cdot 1.3H_2O \cdot 1.0CH_2Cl_2$ (M_r 888.968): C, 39.18; H, 4.38; N, 3.15. Found: C, 39.00; H, 4.20; N, 3.02. Karl Fisher titration calcd for 1.3 H_2O: 2.63. Found: 2.70.

[*cis*-9,10,12,13,15,16,18,19,21,22,30a,31,32,33,34,34a-Hexadecahydro-3,7:24,28-dimetheno-8,11,14,17,20,23,1,30-benzohexaoxadiazacyclodotriacontine-35,36-diolato(2−)-N^1,N^{30},O^{35},O^{36}]dioxouranium·3.3H_2O (5b): eluent CH_2Cl_2:MeOH 30:1; yield 50%; mp 130–132 °C (CH_2Cl_2/petroleum ether); ^1H NMR δ 9.27 (s, 2 H, CH=N), 7.3–7.1 (m, 4 H, H-4, H-6), 6.64 (dd, *J* = 7.8 Hz, 2 H, H-5), 4.7–4.6 (m, 2 H, H-7), 4.5–4.3 (m, 4 H, OCH_2), 4.1–4.0 (m, 4 H, OCH_2), 4.0–3.9 (m, 4 H, OCH_2), 3.8–3.6 (m, 8 H, OCH_2), 2.6–2.4 (m, 2 H, H-8_{eq}), 2.0–1.9 (m, 2 H, H-8_{ax}), 1.9–1.6 (m, 4 H, H-9); ^1H 2D COSY results are depicted in Chart III. ^1H 2D NOESY[11,36] results are depicted in Chart IV. ^{13}C NMR δ 167.9 (d, CH=N), 160.8 (s, C-2), 150.2 (s, C-3), 128.1 (d, C-6), 124.6 (s, C-1), 120.4 (d, C-5), 116.1 (d, C-4), 71.6 (d, C-7), 71.0, 70.5, 70.3, 70.2, 70.0 (t, OCH_2), 27.8 (t, C-8), 21.8 (t, C-9); IR (KBr) 1616 (C=N), 900 (O-U-O) cm^{-1}; mass spectrum (EI), *m*/*z* 824.302 (M^+, calcd 824.303). Anal. Calcd for $C_{30}H_{38}N_2O_{10}U \cdot 3.3H_2O$ (M_r 884.118): C, 40.75; H, 5.08; N, 3.17. Found: C, 40.33; H, 4.62; N, 3.02. Karl Fisher titration calcd for 3.3 H_2O: 6.72. Found: 6.53.

(34) Instructions for use of the Karl Fischer Coulometer 652, Metrohm Herisau, Switzerland.

(35) Receptor **7** and solid urea are equilibrated for 20 h; 1:1 complex formation was concluded from integration of the ^1H NMR spectrum recorded in $CDCl_3$.

(36) Mixing time 0.75 s.

[*cis*-9,10,12,13,15,16,18,19,21,22,24,25,33a,34,35,36,37,37a-Octadecahydro-3,7:27,31-dimetheno-8,11,14,17,20,23,26,1,33-benzoheptaoxadiazacyclopentatriacontine-38,39-diolato-(2-)-N^1,N^{33},O^{38},O^{39}]dioxouranium·2H_2O (5c): eluent CH_2Cl_2:MeOH 20:1; yield 48%; mp 53–55 °C (CH_2Cl_2/petroleum ether); ^{1}H NMR δ 9.27 (s, 2 H, CH=N), 7.3–7.2 (m, 4 H, H-4, H-6), 6.64 (dd, J = 7.8 Hz, 2 H, H-5), 4.6–4.5 (m, 2 H, H-7), 4.5–4.4 (m, 4 H, OCH_2), 4.1–4.0 (m, 4 H, OCH_2), 4.0–3.9 (m, 4 H, OCH_2), 3.9–3.7 (m, 4 H, OCH_2), 3.96 (s, 12 H, OCH_2), 2.6–2.4 (m, 2 H, H-8_{eq}), 2.0–1.9 (m, 2 H, H-8_{ax}), 1.9–1.6 (m, 4 H, H-9); ^{13}C NMR δ 167.7 (d, CH=N), 161.1 (s, C-2), 150.1 (s, C-3), 128.0 (d, C-6), 124.6 (s, C-1), 121.3 (d, C-5), 116.3 (d, C-4), 71.5 (d, C-7), 71.1, 70.8, 70.7, 70.4, 70.3 (t, OCH_2), 27.9 (t, C-8), 21.8 (t, C-9); IR (KBr) 1615 (C=N), 897 (O–U–O) cm^{-1}; mass spectrum (EI), m/z 868.335 (M^+, calcd 868.330). Anal. Calcd for $C_{32}H_{42}N_2O_{11}U·2H_2O$ (M_r 904.751): C, 42.48; H, 5.12; N, 3.10. Found: C, 42.41; H, 5.12; N, 2.78. Karl Fisher titration calcd for 2.0 H_2O: 3.98. Found: 3.58.

[*cis*-9,10,12,13,15,16,18,19,21,22,24,25,27,28,36a,37,38,39,-40,40a-Eicosahydro-3,7:30,34-dimetheno-8,11,14,17,20,23,-26,29,1,36-benzooctaoxadiazacyclooctatriacontine-41,42-diolato(2-)-N^1,N^{36},O^{41},O^{42}]dioxouranium·2H_2O (5d): eluent CH_2Cl_2:MeOH 15:1; yield 47%; mp 55–58 °C (CH_2Cl_2/petroleum ether); ^{1}H NMR δ 9.27 (s, 2 H, CH=N), 7.3–7.2 (m, 4 H, H-4, H-6), 6.64 (dd, J = 7.8 Hz, 2 H, H-5), 4.7–4.6 (m, 2 H, H-7), 4.5–4.4 (m, 4 H, OCH_2), 4.1–4.0 (m, 4 H, OCH_2), 4.0–3.9 (m, 4 H, OCH_2), 3.9–3.8 (m, 4 H, OCH_2), 3.8–3.5 (m, 12 H, OCH_2), 2.5–2.3 (m, 2 H, H-8_{eq}), 2.0–1.8 (m, 2 H, H-8_{ax}), 1.8–1.6 (m, 4 H, H-9); ^{13}C NMR δ 167.7 (d, CH=N), 161.2 (s, C-2), 150.0 (s, C-3), 128.0 (d, C-6), 124.6 (s, C-1), 122.0 (d, C-5), 116.5 (d, C-4), 71.4 (d, C-7), 71.1, 70.9, 70.8, 70.7, 70.6, 70.2 (t, OCH_2), 27.8 (t, C-8), 21.8 (t, C-9); IR (KBr) 1614 (C=N), 897 (O–U–O) cm^{-1}; mass spectrum (EI), m/z 912.360 (M^+, calcd 912.356). Anal. Calcd for $C_{34}H_{46}N_2O_{12}U·2H_2O$ (M_r 948.804): C, 43.04; H, 5.31; N, 2.95. Found: C, 43.20; H, 5.37; N, 2.64. Karl Fischer titration calcd for 2.0 H_2O: 3.80. Found: 3.41.

General Procedures for the Synthesis of Complexes 6. Method A. To a solution of **5** (0.05 mmol) in MeOH (30 mL) was added an excess of guest (0.5–1.0 mmol). Upon standing at room temperature the complexes slowly precipitated after partial evaporation of the solvent. Pure complexes were obtained after filtration or decantation and thoroughly drying in vacuo.

Method B. From a solution of **5** in MeOH (as in method A) the complex precipitated at −30 °C. Isolation was performed as described for method A.

Method C. To a solution of **5** (0.05 mmol) in $CHCl_3$ (3 mL) was added an excess of guest (0.5 mmol). The complex was precipitated by slow diffusion of petroleum ether in the $CHCl_3$ layer. Isolation was performed as described for method A.

[*cis*-9,10,12,13,15,16,18,19,21,22,30a,31,32,33,34,34a-Hexadecahydro-3,7:24,28-dimetheno-8,11,14,17,20,23,1,30-benzohexaoxadiazacyclodotriacontine-35,36-diolato(2-)-N^1,N^{30},O^{35},O^{36}]dioxouranium·urea·1.7H_2O (6b·urea): method A; yield 88%; mp 225–230 °C (MeOH); ^{1}H NMR δ 9.25 (s, 2 H, CH=N), 7.4–7.0 (br s, 4 H, NH_2), 7.1–7.0 (m, 4 H, H-4, H-6), 6.59 (dd, J = 7.8 Hz, 2 H, H-5), 4.7–4.6 (m, 2 H, H-7), 4.4–4.3 (m, 4 H, OCH_2), 4.1–3.9 (m, 4 H, OCH_2), 3.8–3.6 (m, 12 H, OCH_2), 2.6–2.4 (m, 2 H, H-8_{eq}), 2.0–1.6 (m, 6 H, H-8_{ax}, H-9); see supplementary material for 2D COSY spectrum; ^{13}C NMR spectrum could not be recorded due to the low solubility of the complex; IR (KBr) 1651 (C=O), 1615 (C=N), 898 (O–U–O) cm^{-1}; mass spectrum (FAB), m/z 885.6 ((M + CH_4N_2O + H)$^+$, calcd for $C_{31}H_{43}N_4O_{11}U$ 885.3), 825.6 ((M + H)$^+$, calcd for $C_{30}H_{38}N_2O_{10}U$ 825.3). Anal. Calcd for $C_{30}H_{38}N_2O_{10}U·CH_4N_2O·1.7H_2O$ (M_r 915.439): C, 40.67; H, 5.00; N, 6.12. Found: C, 40.84; H, 4.50; N, 6.39. Karl Fischer titration calcd for 1.7 H_2O: 3.35. Found: 3.41.

[*cis*-9,10,12,13,15,16,18,19,21,22,30a,31,32,33,34,34a-Hexadecahydro-3,7:24,28-dimetheno-8,11,14,17,20,23,1,30-benzohexaoxadiazacyclodotriacontine-35,36-diolato(2-)-N^1,N^{30},O^{35},O^{36}]dioxouranium·hydroxyurea (6b·hydroxyurea): method A; yield 65%, mp 218–220 °C ($CHCl_3$/MeOH); ^{1}H NMR δ 9.9–9.8 (br s, 1 H, hydroxyurea), 9.27 (s, 2 H, CH=N), 8.25–8.15 (br s, 1 H, hydroxyurea), 7.17 (d, J = 7.8 Hz, 4 H, H-4, H-6), 6.61 (dd, J = 7.8 Hz, 2 H, H-5), 4.7–4.6 (m, 2 H, H-7), 4.6–4.5 (m, 4 H, OCH_2), 4.1–4.0 (m, 4 H, OCH_2), 3.9–3.8 (m, 4 H, OCH_2), 3.8–3.7 (m, 4 H, OCH_2), 3.68 (s, 8 H, OCH_2), 2.6–2.4 (m, 2 H, H-8_{eq}), 2.0–1.9 (m, 2 H, H-8_{ax}), 1.9–1.6 (m, 4 H, H-9); IR (KBr) 1642 (C=O), 1616 (C=N), 899 (O–U–O) cm^{-1}; mass spectrum (FAB), m/z 901.3 ((M + $CH_4N_2O_2$ + H)$^+$, calcd for $C_{31}H_{43}N_4O_{12}U$ 901.3), 825.3 ((M + H)$^+$, calcd for $C_{30}H_{38}N_2O_{10}U$ 825.3). Anal. Calcd for $C_{30}H_{38}N_2O_{10}U·CH_4N_2O_2$ (M_r 900.717): C, 41.34; H, 4.70; N, 6.22. Found: C, 41.31; H, 4.67; N, 5.73.

[*cis*-9,10,12,13,15,16,18,19,21,22,30a,31,32,33,34,34a-Hexadecahydro-3,7:24,28-dimetheno-8,11,14,17,20,23,1,30-benzohexaoxadiazacyclodotriacontine-35,36-diolato(2-)-N^1,N^{30},O^{35},O^{36}]dioxouranium·DMSO (6b·DMSO): method C; yield 48%; mp 242–248 °C (CH_3OH); ^{1}H NMR δ 9.24 (s, 2 H, CH=N), 7.3–7.1 (m, 4 H, H-4, H-6), 6.63 (dd, J = 7.7 Hz, 2 H, H-5), 4.7–4.6 (m, 2 H, H-7), 4.6–4.4 (m, 4 H, OCH_2), 4.1–4.0 (m, 4 H, OCH_2), 4.0–3.7 (m, 12 H, OCH_2), 3.3–2.6 (br s, 6 H, CH_3), 2.5–2.3 (m, 2 H, H-8_{eq}), 2.0–1.8 (m, 2 H, H-8_{ax}), 1.9–1.6 (m, 4 H, H-9); IR (KBr) 1618 (C=N), 997 (S=O), 891 (O–U–O) cm^{-1}; mass spectrum (EI), m/z 824.308 (M^+, calcd for $C_{30}H_{40}N_2O_{10}U$ 824.303), 78.014 (M^+, calcd for C_2H_6OS 78.014). Anal. Calcd for $C_{30}H_{38}N_2O_{10}U·C_2H_6OS$ (M_r 902.796): C, 42.57; H, 4.91; N, 3.10; S, 3.55. Found: C, 42.40; H, 4.86; N, 3.05; S, 3.54.

[*cis*-9,10,12,13,15,16,18,19,21,22,24,25,33a,34,35,36,37,37a-Octadecahydro-3,7:27,31-dimetheno-8,11,14,17,20,23,26,1,33-benzoheptaoxadiazacyclopentatriacontine-38,39-diolato-(2-)-N^1,N^{33},O^{38},O^{39}]dioxouranium·urea (6c·urea): method A; yield 90%; mp 257–259 °C (CH_3OH); ^{1}H NMR δ 9.26 (s, 2 H, CH=N), 7.68 (br s, 2 H, urea), 7.2–7.1 (m, 4 H, H-4, H-6), 6.59 (dd, J = 7.8 Hz, 2 H, H-5), 6.54 (br s, 2 H, urea), 4.9–4.8 (m, 2 H, OCH_2), 4.6–4.5 (m, 2 H, H-7), 4.5–4.4 (m, 2 H, OCH_2), 4.1–3.9 (m, 4 H, OCH_2), 3.9–3.6 (m, 16 H, OCH_2), 2.65–2.45 (m, 2 H, H-8_{eq}), 2.0–1.9 (m, 2 H, H-8_{ax}), 1.8–1.6 (m, 4 H, H-9); ^{13}C NMR δ 167.8 (d, C=N), 160.5 (s, C-2), 150.5 (s, C-3), 127.2 (d, C-6), 124.2 (s, C-1), 119.0 (d, C-5), 115.5 (d, C-4), 71.6 (d, C-7), 70.5, 70.5, 70.2, 70.0, 69.9, 68.8 (t, OCH_2), 28.3 (t, C-8), 21.7 (t, C-9); IR (KBr) 1648 (C=O), 1619 (C=N), 894 (O–U–O) cm^{-1}; mass spectrum (FAB), m/z 928.5 ((M + CH_4N_2O)$^+$, calcd for $C_{33}H_{46}N_4O_{12}U$ 928.4), 869.3 ((M + H)$^+$, calcd for $C_{32}H_{43}N_2O_{22}U$ 869.3). Anal. Calcd for $C_{32}H_{42}N_2O_{11}U·CH_4N_2O$ (M_r 928.776): C, 42.68; H, 4.99; N, 6.03. Found: C, 42.24; H, 4.84; N, 5.81.

[*cis*-9,10,12,13,15,16,18,19,21,22,24,25,33a,34,35,36,37,37a-Octadecahydro-3,7:27,31-dimetheno-8,11,14,17,20,23,26,1,33-benzoheptaoxadiazacyclopentatriacontine-38,39-diolato-(2-)-N^1,N^{33},O^{38},O^{39}]dioxouranium·hydroxyurea·2H_2O (6c·hydroxyurea): method A; yield 86%; mp 227–228 °C (MeOH); ^{1}H NMR δ 9.88 (s, 1 H, hydroxyurea), 9.27 (s, 2 H, CH=N), 8.70 (br s, 1 H, hydroxyurea), 7.92 (s, 1 H, hydroxyurea), 7.39 (br s, 1 H, hydroxyurea), 7.2–7.1 (m, 4 H, H-4, H-6), 6.61 (dd, J = 7.7 Hz, 2 H, H-5), 4.70–4.65 (m, 2 H, H-7), 4.65–4.55 (m, 2 H, OCH_2), 4.55–4.45 (m, 2 H, OCH_2), 4.1–4.0 (m, 4 H, OCH_2), 3.89 (s, 4 H, OCH_2), 3.73 (s, 4 H, OCH_2), 3.6–3.5 (m, 8 H, OCH_2), 2.55–2.45 (m, 2 H, H-8_{eq}), 2.0–1.9 (m, 2 H, H-8_{ax}), 1.9–1.6 (m, 4 H, H-9); IR (KBr) 1646 (C=O), 1616 (C=N), 896 (O–U–O) cm^{-1}; mass spectrum (FAB), m/z 945.7 ((M + $CH_4N_2O_2$ + H)$^+$, calcd for $C_{33}H_{46}N_4O_{13}U$ 945.3), 869.7 ((M + H)$^+$, calcd for $C_{32}H_{43}N_2O_{11}U$ 869.3). Anal. Calcd for $C_{32}H_{42}N_2O_{11}U·CH_4N_2O_2$ (M_r 944.775): C, 41.95; H, 4.91; N, 5.93. Found: C, 42.16; H, 4.79; N, 5.47.

[*cis*-9,10,12,13,15,16,18,19,21,22,24,25,33a,34,35,36,37,37a-Octadecahydro-3,7:27,31-dimetheno-8,11,14,17,20,23,26,1,33-benzoheptaoxadiazacyclopentatriacontine-38,39-diolato-(2-)-N^1,N^{33},O^{38},O^{39}]dioxouranium·acetamide (6c·acetamide): method C;[37] yield 45%; mp 98–103 °C ($CHCl_3$/petroleum ether); ^{1}H NMR δ 9.28 (s, 2 H, CH=N), 7.2–7.1 (m, 4 H, H-4, H-5), 6.62 (dd, J = 7.8 Hz, H-5), 4.65–4.55 (m, 2 H, H-7), 4.55–4.40 (m, 4 H, OCH_2), 4.1–3.9 (m, 4 H, OCH_2), 3.8–3.5 (m, 16 H, OCH_2), 2.6–2.5 (m, 2 H, H-8_{eq}), 2.5–2.0 (br s, 3 H, CH_3), 2.0–1.6 (m, 6 H, H-8_{ax}, H-9); IR (KBr) 1659 (C=O), 1613 (C=N), 892 (O–U–O) cm^{-1}; mass spectrum (EI), m/z 868.321 (M^+, calcd for $C_{32}H_{42}N_2O_{11}U$ 868.330), 59.036 (M^+, calcd for C_2H_5NO 59.037).

[*cis*-9,10,12,13,15,16,18,19,21,22,24,25,33a,34,35,36,37,37a-Octadecahydro-3,7:27,31-dimetheno-8,11,14,17,20,23,26,1,33-benzoheptaoxadiazacyclopentatriacontine-38,39-diolato-(2-)-N^1,N^{33},O^{38},O^{39}]dioxouranium·formamide (6c·form-

(37) The elemental analysis is not correct; the complex is contaminated with a small amount of free guest.

amide): method C;[37] yield 77%; mp 75–78 °C ($CHCl_3$/petroleum ether); ^1H NMR δ 9.29 (s, 2 H, CH=N), 7.2–7.1 (m, 4 H, H-4, H-6), 6.64 (dd, J = 7.8 Hz, 2 H, H-5), 4.7–4.6 (m, 2 H, H-7), 4.5–4.4 (m, 4 H, OCH_2), 4.1–4.0 (m, 4 H, OCH_2), 4.0–3.9 (m, 4 H, OCH_2), 3.8–3.7 (m, 4 H, OCH_2), 3.70–3.65 (m, 4 H, OCH_2), 3.65–3.60 (m, 4 H, OCH_2); IR (KBr) 1676 (C=O), 1612 (C=N), 897 (O–U–O) cm^{-1}; mass spectrum (EI), m/z 868.328 (M^+, calcd for $C_{32}H_{42}N_2O_{11}U$ 868.330), 45.024 (M^+, calcd for CH_3NO 45.022).

[*cis*-9,10,12,13,15,16,18,19,21,22,24,25,33a,34,35,36,37,37a-Octadecahydro-3,7:27,31-dimetheno-8,11,14,17,20,23,26,1,33-benzoheptaoxadiazacyclopentatriacontine-38,39-diolato-(2–)-N^1,N^{33},O^{38},O^{39}]dioxouranium·DMSO (6c·DMSO): method C; yield 44%; mp 163–169 °C ($CHCl_3$/petroleum ether); ^1H NMR δ 9.27 (s, 2 H, CH=N), 7.25–7.15 (m, 4 H, H-4, H-6), 6.64 (dd, J = 7.8 Hz, 2 H, H-5), 4.7–4.6 (m, 2 H, H-7), 4.5–4.4 (m, 4 H, OCH_2), 4.1–4.0 (m, 4 H, OCH_2), 4.0–3.9 (m, 10 H, OCH_2, CH_3), 3.9–3.8 (m, 4 H, OCH_2), 3.69 (s, 8 H, OCH_2), 2.6–2.4 (m, 2 H, H-8_{eq}), 2.0–1.9 (m, 4 H, H-8_{ax}), 1.9–1.6 (m, 4 H, H-9); IR (KBr) 1617 (C=N), 999 (S=O), 895 (O–U–O) cm^{-1}; mass spectrum (EI), m/z 868.325 (M^+, calcd for $C_{32}H_{42}N_2O_{11}U$ 868.330), 78.014 (M^+, calcd for C_2H_6OS 78.014). Anal. Calcd for $C_{32}H_{42}N_2O_{11}U·C_2H_6OS$ (M_r 946.849): C, 43.14; H, 5.11; N, 2.96. Found: C, 42.97; H, 5.31; N, 2.86.

[*cis*-9,10,12,13,15,16,18,19,21,22,24,25,33a,34,35,36,37,37a-Octadecahydro-3,7:27,31-dimetheno-8,11,14,17,20,23,26,1,33-benzoheptaoxadiazacyclopentatriacontine-38,39-diolato-(2–)-N^1,N^{33},O^{38},O^{39}]dioxouranium·*N*-methylurea (6c·*N*-methylurea): method C; yield 50%; mp 235–236 °C ($CHCl_3$/petroleum ether); ^1H NMR δ 9.27 (CH=N), 7.2–7.1 (m, 4 H, H-4, H-6), 6.61 (dd, J = 7.8 Hz, 2 H, H-5), 4.7–4.6 (m, 2 H, H-7), 4.5–4.4 (m, 4 H, OCH_2), 4.1–4.0 (m, 4 H, OCH_2), 3.9–3.6 (m, 19 H, OCH_2 and CH_3), 2.6–2.5 (m, 2 H, H-8_{eq}), 2.0–1.6 (m, 6 H, H-8_{ax}, H-9); IR (KBr) 1637 (C=O), 1618 (C=N), 896 (O–U–O) cm^{-1}; mass spectrum (EI), m/z 868.321 (M^+, calcd for $C_{32}H_{42}N_2O_{11}$ 868.330), 74.048 (M^+, calcd for $C_2H_6N_2O$ 74.048). Anal. Calcd for $C_{32}H_{42}N_2O_{11}U·C_2H_6N_2O·0.6H_2O$ (M_r 953.612): C, 42.82; H, 5.20; N, 5.87. Found: C, 42.53; H, 4.87; N, 5.60. Karl Fischer titration calcd for 0.6 H_2O: 1.13. Found: 1.09.

[*cis*-9,10,12,13,15,16,18,19,21,22,24,25,27,28,36a,37,38,39,-40,40a-Eicosahydro-3,7:30,34-dimetheno-8,11,14,17,20,23,-26,29,1,36-benzooctaoxadiazacyclooctatriacontine-41,-42-diolato(2–)-N^1,N^{36},O^{41},O^{42}]dioxouranium·urea·0.4$CHCl_3$ (6d·urea): method B. Over a period of a few days DIP (75 mL) was added: yield 29%; mp 200–202 °C (MeOH/DIP). ^1H NMR spectrum is identical with the spectrum of the complex obtained via method C. Method C: urea added in MeOH (1 mL). Upon standing urea and the complex both precipitated. Solids were filtered off and the complex was redissolved in $CHCl_3$/petroleum ether (1:2) (see ref 2a for the low solubility of urea in $CHCl_3$; by addition of petroleum ether the solubility of urea is even lower). After removal of solid urea by filtration pure complex was obtained upon concentration in vacuo: yield 92%; mp 207–210 °C ($CHCl_3$/petroleum ether); ^1H NMR δ 9.26 (s, 2 H, CH=N), 7.5–6.5 (br s, 4 H, urea), 7.2–7.1 (m, 4 H, H-4, H-6), 6.59 (dd, J = 7.8 Hz, 2 H, H-5), 4.6–4.5 (m, 4 H, H-7, OCH_2), 4.5–4.4 (m, 2 H, OCH_2), 4.2–4.0 (m, 4 H, OCH_2), 3.8–3.5 (m, 20 H, OCH_2), 2.6–2.4 (m, 2 H, H-8_{eq}), 2.0–1.9 (m, 2 H, H-8_{ax}), 1.9–1.6 (m, 4 H, H-9); IR (KBr) 1640 (C=O), 1614 (C=N), 894 (O–U–O) cm^{-1}; mass spectrum (EI), m/z 912.367 (M^+, calcd for $C_{34}H_{46}N_2O_{12}U$ 912.356), 60.034 (M^+, calcd for CH_4N_2O 60.032). Anal. Calcd for $C_{34}H_{46}N_2O_{12}U·CH_4N_2O·0.4CHCl_3$ (M_r 1020.580): C, 42.04; H, 5.34; N, 5.60. Found: C, 41.80; H, 4.87; N, 5.28.

[*cis*-9,10,12,13,15,16,18,19,21,22,24,25,27,28,36a,37,38,39,-40,40a-Eicosahydro-3,7:30,34-dimetheno-8,11,14,17,20,23,26,-29,1,36-benzooctaoxadiazacyclooctatriacontine-41,42-diolato(2–)-N^1,N^{36},O^{41},O^{42}]dioxouranium·hydroxyurea·1.5CH_2Cl_2 (6d·hydroxyurea): method C. Hydroxyurea was added in MeOH (1 mL), and hydroxyurea and the complex both precipitated. Solids were filtered off and the residue was redissolved in CH_2Cl_2/petroleum ether (1:1). After removal of solid hydroxyurea by filtration, pure complex was obtained upon concentration in vacuo: yield 40%; mp 202–205 °C (CH_2Cl_2/petroleum ether); ^1H NMR δ 9.56 (s, 1 H, hydroxyurea), 9.25 (s, 2 H, CH=N), 8.82 (br s, 1 H, hydroxyurea), 7.98 (s, 1 H, hydroxyurea), 7.50 (br s, 1 H, hydroxyurea), 7.2–7.1 (m, 4 H, H-4, H-6), 6.59 (dd, J = 7.8 Hz, 2 H, H-5), 5.25 (s, 1.5 CH_2Cl_2), 4.8–4.7 (m, 2 H, OCH_2), 4.6–4.5 (m, 4 H, H-7, OCH_2), 4.1–4.0 (m, 4 H, OCH_2), 3.9–3.8 (m, 4 H, OCH_2), 3.8–3.7 (m, 4 H, OCH_2), 3.7–3.6 (m, 4 H, OCH_2), 3.6–3.5 (m, 4 H, OCH_2), 3.48 (s, 4 H, OCH_2), 2.6–2.4 (m, 2 H, H-8_{eq}), 2.0–1.9 (m, 2 H, H-8_{ax}), 1.9–1.6 (m, 4 H, H-9); IR (KBr) 1664 (C=O), 1610 (C=N), 894 (O–U–O) cm^{-1}; mass spectrum (FAB), m/z 989.4 ((M + $CH_4N_2O_2$ + H)$^+$, calcd for $C_{35}H_{50}N_4O_{14}U$ 989.4), 913.5 ((M + H)$^+$ calcd for $C_{34}H_{46}N_2O_{12}U$ 913.4). Anal. Calcd for $C_{34}H_{46}N_2O_{12}U·CH_4N_2O_2·1.5CH_2Cl_2$ (M_r 1114.716): C, 39.33; H, 4.79; N, 5.03. Found: C, 38.99; H, 4.79; N, 4.94.

[*cis*-9,10,12,13,15,16,18,19,21,22,24,25,27,28,36a,37,38,39,-40,40a-Eicosahydro-3,7:30,34-dimetheno-8,11,14,17,20,23,-26,29,1,36-benzooctaoxadiazacyclooctatriacontine-41,42-diolato(2–)-N^1,N^{36},O^{41},O^{42}]dioxouranium·DMSO·$CHCl_3$ (6d·DMSO): method B; yield 60%; mp 78–80 °C (MeOH). The ^1H NMR spectrum is identical with the spectrum of the complex obtained via method C: yield 50%; mp 80 °C ($CHCl_3$/petroleum ether); ^1H NMR δ 9.28 (s, 2 H, CH=N), 7.25–7.20 (m, 4 H, H-4, H-6), 6.64 (dd, J = 7.8 Hz, 2 H, H-6), 4.7–4.6 (m, 2 H, H-7), 4.5–4.4 (m, 4 H, OCH_2), 4.1–4.0 (m, 4 H, OCH_2), 4.0–3.5 (m, 26 H, OCH_2, DMSO), 2.6–2.4 (m, 2 H, H-8_{eq}), 2.0–1.9 (m, 2 H, H-8_{ax}), 1.9–1.7 (m, 4 H, H-9); IR (KBr) 1614 (C=N), 1006 (S=O), 891 (O–U–O) cm^{-1}; mass spectrum (EI), m/z 912.348 (M^+, calcd for $C_{34}H_{46}N_2O_{12}U$ 912.356), 78.014 (M^+, calcd for C_2H_6OS 78.014). Anal. Calcd for $C_{34}H_{46}N_2O_{12}U·C_2H_6OS·CHCl_3$ (M_r 1110.280): C, 40.03; H, 4.81; N, 2.82; S, 2.89. Found: C, 39.89; H, 4.72; N, 2.43; S, 2.49.

[*cis*-9,10,12,13,15,16,18,19,21,22,24,25,27,28,36a,37,38,39,-40,40a-Eicosahydro-3,7:30,34-dimetheno-8,11,14,17,20,23,-26,29,1,36-benzooctaoxadiazacyclooctatriacontine-41,42-diolato(2–)-N^1,N^{36},O^{41},O^{42}]dioxouranium·*N*-methylurea·2H_2O) (6d·*N*-methylurea): method C; yield 90%; mp 179–182 ($CHCl_3$/petroleum ether). The ^1H NMR spectrum is identical with the spectrum of the complex obtained via method B: yield 14%; mp 173–176 °C (MeOH); ^1H NMR δ 9.27 (s, 2 H, CH=N), 7.2–7.1 (m, 4 H, H-4, H-6), 6.60 (dd, J = 7.7 Hz, 2 H, H-5), 4.7–4.6 (m, 2 H, H-7), 4.5–4.3 (m, 4 H, OCH_2), 4.1–3.9 (m, 4 H, OCH_2), 3.9–3.5 (m, 23 H, OCH_2, CH_3), 2.6–2.4 (m, 2 H, H-8_{eq}), 2.0–1.6 (m, 6 H, H-8_{ax}, H-9); IR (KBr) 1639 (C=O), 1613 (C=N), 893 (O–U–O) cm^{-1}; mass spectrum (EI), m/z 912.355 (M^+, calcd for $C_{34}H_{46}N_2O_{12}U$ 912.356), 74.048 (M^+, calcd for $C_2H_6N_2O$ 74.048). Anal. Calcd for $C_{34}H_{46}N_2O_{12}U·C_2H_6N_2O·2.0H_2O$ (M_r 1022.889): C, 42.27; H, 5.52; H, 5.48. Found: C, 42.02; H, 5.07; N, 5.10.

[*cis*-9,10,12,13,15,16,18,19,21,22,24,25,27,28,36a,37,38,39,-40,40a-Eicosahydro-3,7:30,34-dimetheno-8,11,14,17,20,23,-26,29,1,36-benzooctaoxadiazacyclooctatriacontine-41,42-diolato(2–)-N^1,N^{36},O^{41},O^{42}]dioxouranium·formamide (6d·formamide): method C; yield 80%; mp 169–170 °C ($CHCl_3$/petroleum ether); ^1H NMR δ 9.29 (s, 2 H, CH=N), 7.22–7.16 (m, 4 H, H-4, H-6), 6.65 (dd, J = 7.8 Hz, 2 H, H-5), 4.7–4.6 (m, 2 H, H-7), 4.6–4.4 (m, 4 H, OCH_2), 4.1–4.0 (m, 4 H, OCH_2), 3.9–3.8 (m, 4 H, OCH_2), 3.8–3.6 (m, 16 H, OCH_2), 2.6–2.4 (m, 2 H, H-8_{eq}), 2.0–1.6 (m, 6 H, H-8_{ax}, H-9); IR (KBr) 1689 (C=O), 1616 (C=N), 896 (O–U–O) cm^{-1}; mass spectrum (EI), m/z 912.361 (M^+, calcd for $C_{32}H_{46}N_2O_{12}U$ 912.356), 45.022 (M^+, calcd for CH_3NO 45.022). Anal. Calcd for $C_{34}H_{46}N_2O_{12}U·CH_3NO·0.6CHCl_3$ (M_r 1029.441): C, 41.53; H, 4.86; N, 4.08. Found: C, 41.23; H, 4.74; N, 5.16.

[*cis*-9,10,12,13,15,16,18,19,21,22,24,25,27,28,36a,37,38,39,-40,40a-Eicosahydro-3,7:30,34-dimetheno-8,11,14,17,20,23,-26,29,1,36-benzooctaoxadiazacyclooctatriacontine-41,42-diolato(2–)-N^1,N^{36},O^{41},O^{42}]dioxouranium·acetamide (6d·acetamide): method C;[37] yield 65%; mp 176–180 °C ($CHCl_3$/petroleum ether); ^1H NMR δ 9.29 (s, 2 H, CH=N), 7.20–7.10 (m, 4 H, H-4, H-6), 6.63 (dd, J = 7.8 Hz, 2 H, H-5), 4.7–4.6 (m, 2 H, H-7), 4.6–4.4 (m, 4 H, OCH_2), 4.1–3.9 (m, 4 H, OCH_2), 3.80–3.78 (m, 4 H, OCH_2), 3.75–3.72 (m, 4 H, OCH_2), 3.69–3.67 (m, 4 H, OCH_2), 3.61–3.58 (m, 4 H, OCH_2), 3.53 (s, 4 H, OCH_2), 2.6–2.4 (m, 2 H, H-8_{eq}), 2.05 (s, 3 H, CH_3), 2.0–1.6 (m, 6 H, H-8_{ax}, H-9); IR (KBr) 1667 (C=O), 1615 (C=N), 893 (O–U–O) cm^{-1}; mass spectrum (EI), m/z 912.357 (M^+, calcd for $C_{34}H_{46}N_2O_{12}U$ 912.356), 59.037 (M^+, calcd for C_2H_5NO 59.037).

^1H NMR Spectroscopy. *Dilution experiments* were performed with the urea complexes of **5b–d** in $CDCl_3$ in the concentration range 4.0–0.4 mM. Estimated accuracy is 0.05 equiv. Results are presented in the Results and Discussion section.

Competition experiments were performed by mixing 1 equiv of a free ligand with 1 equiv of a urea complex of another ligand

in the concentration range 4.0–0.4 mM. Estimated accuracy is 0.05 equiv. Results are presented in Table II.

Liquid–Liquid Extraction Experiments. A 4 mM solution of metallomacrocycle **5** in $CDCl_3$ (1 mL) was equilibrated for 20 h with an aqueous solution of 1.0, 0.1, or 0.05 M urea (1 mL). The metallomacrocycle **5** containing organic layer was analyzed with ^1H NMR spectroscopy. The complex **6**/free ligand **5** ratio was determined as for the solid–liquid extraction experiments. Complex **6d**·urea gives dynamic exchange on the 250-MHz NMR time scale in water-saturated $CDCl_3$. For this complex we determined the amount of urea differently. First, the water layer was separated off and 1 equiv of **5c** was added. Second, within 2 h all urea has exchanged and is present as **6c**·urea. Finally we know the amount of urea from integration. Estimated accuracy is 0.10 equiv. Results are given in Table III.

Solid–Liquid Extraction Experiments. A 2 mM solution of metallomacrocycle **5** in $CDCl_3$ (1 mL) was equilibrated for 20 h with solid urea. The metallomacrocycle-containing organic layer was analyzed with ^1H NMR spectroscopy. Determinations of the complex **6**/free ligand **5** ratio were easy because the exchange is slow on the 250-MHz NMR time scale. Estimated accuracy is 0.05 equiv. Results are given in the Results and Discussion section.

Crystal Structure Determination. The crystal structures of **1**(n=5)·MeOH, **6b**·urea, and **6d**·urea were determined with X-ray diffraction methods.

Reflections were measured in the $\omega/2\theta$ scan mode, using graphite-monochromated Mo Kα radiation at 148 K (**1**(n=5)·MeOH) or 178 K (**6b**·urea and **6d**·urea). Lattice parameters were determined by least squares from 25 centered reflections. Intensities were corrected for decay during data collection using three control reflections, measured every hour.

The uranium cation was located by the Patterson method and the rest of the non-hydrogen atoms by successive difference Fourier syntheses. Reflections with $F_o^2 > 3\sigma(F_o^2)$ were considered observed and were included in the refinement (on F) by full-matrix least squares. Weights were calculated as $w = 4F_o^2/\sigma^2(F_o^2)$, $\sigma^2(F_o^2) = \sigma^2(I) + (pF_o^2)^2$, $\sigma(I)$ based on counting statistics and p an instability factor obtained from plots of F_o vs weighted error. An empirical absorption correction, using DIFABS,[38] was performed. In all three structures the uranium atoms were refined with anisotropic thermal parameters. All atoms of **1**(n=5)·MeOH (four methanol molecules are present in the structure; Figure 1) were refined isotropically except the apical oxygens, which were refined anisotropically. The chlorine (from $CHCl_3$; solvent molecule is not depicted in Figure 3), oxygen (except the apical oxygens), and urea nitrogen atoms of the **6b**·urea complex were refined anisotropically; the rest of the atoms were refined isotropically. The metallomacrocycle (except the carbon atom which is placed in two positions), the encapsulated urea, and the heteroatoms of the urea molecule outside the cavity were refined anisotropically; the rest of the atoms of **6d**·urea (2 urea molecules are present; Figure 4) were refined isotropically. Parameters refined were scale factor, positional and thermal parameters. In **1**(n=5)·MeOH and **6b**·urea all hydrogen atoms were placed at 0.95 Å and treated as riding on their parent carbon or nitrogen atom; in **6d**·urea only the urea hydrogens were included. The difference Fourier maps of **1**(n=5)·MeOH and **6b**·urea showed no significant features. The map of **6d**·urea showed 11 peaks, in the large channel between adjacent complexes (not shown in Figure 4). These peaks, treated as carbons in the refinement, are most probably due to disordered solvent molecules. The crystal is not stable in air at room temperature due to loss of (a) solvent molecule(s). All calculations were done using SDP.[39] Results are presented in the Results and Discussion section and in Table VII.

Calculations. Ab initio and semiempirical calculations were performed on a system consisting of a planar urea molecule and a point charge at a distance of 2.4 Å from the carbonyl oxygen (approximate distance between the carbonyl oxygen and uranium found in **1**(n=5)·urea,[4b] **6b**·urea, and **6d**·2urea), with different coordination angles C=O···+. The internal degrees of freedom of urea were optimized in the calculations, while the molecule was kept planar. The coordination of the point charge was planar (i.e., in plane of the urea) or perpendicular (i.e., in the mirror plane perpendicular to the urea). The ab initio calculations were performed with the program GAMESS[40] with the 6-31G basis-set; the program was locally modified for a point-charge option included in the Z-matrix definition of the system. Two different point-charge models were used: one with a very sharply peaked s function, which cannot accommodate any electron density, i.e., no charge transfer to the point-charge is possible; the other point-charge model has H-atom basis functions, which allow charge transfer, as evidenced by Mulliken population analysis. The semiemperical calculations were performed with the AM1 method,[41] incorporated in the AMPAC program.[42] As a point charge the so-called "sparkle" was used, an ionic point charge that does not allow charge transfer.

Table VII. Crystal Data and Data Collection Parameters

compd	**1**(n=5)·MeOH	**6b**·urea	**6d**·urea
formula	$C_{38}H_{56}N_2O_{16}U$	$C_{32}H_{43}Cl_3N_3O_{10}U$	$C_{36}H_{54}N_6O_{14}U$
fw	1034.89	947.10	1032.88
lattice group	monoclinic	monoclinic	monoclinic
space group	$P2_1/n$	$P2_1/c$	$C2/c$
T (K)	148	173	173
cell dimensions			
a (Å)	16.478 (8)	18.376 (8)	40.642 (4)
b (Å)	13.748 (5)	16.410 (2)	11.814 (3)
c (Å)	18.154 (8)	12.462 (2)	24.375 (2)
β (deg)	92.82 (3)	95.26 (2)	127.28 (2)
V (Å^3)	4108 (5)	3742 (3)	9312 (6)
Z	4	4	8
D_c (g/cm^3)	1.67	1.73	1.47[a]
F (000)	2072	1916	4128[a]
μ (cm^{-1})	38.2	43.8	33.7[a]
θ range (deg)	3.0–22.5	3.0–22.5	3.0–22.5
no. of unique refln measd	4737	5144	6251
obsd [$I > 3\sigma(I)$]	2970	2617	4556
no. of variables	245	285	536
R (%)	5.8	7.8	8.2
R_w (%)	6.8	7.8	9.3
weighting factor p	0.04	0.05	0.04

[a] Calculated for the given formula; disordered solvent molecules are not taken into account.

Electrochemistry. The polarographic measurements were carried out with a Metrohm Polarecord E506 polarograph in conjunction with a E505 polarographic stand. This polarograph was operated in the three-electrode mode with a dropping mercury electrode (DME) as cathode, a platinum wire as auxiliary electrode, and an Ag/AgCl reference electrode (Metrohm 6.0724.140). The reference electrode was filled with 0.1 M $Et_4N^+Cl^-$ (Merck, synthetic quality, recrystallized from EtOH) in MeOH (Merck, pa quality). The measurements were performed at 20 ± 1 °C in a 0.1 M solution of $Et_4N^+ClO_4^-$ (Fluka, purum) in CH_3CN (Merck, DNA synthesis quality). According to a Karl Fischer titration 0.037% (0.15 M) H_2O was present in the CH_3CN. The reference electrode was brought into contact with the sample via a double salt bridge of the following configuration:

$$Ag/AgCl{:}Et_4N^+Cl^- – MeOH{:}Et_4N^+ClO_4^- – CH_3CN{:}sample$$

The characteristics of the DME electrode glass capillary were m = 0.808 mg/s, natural drop time = 6.81 s at open circuit in 0.1 M $Et_4N^+ClO_4^-/CH_3CN$, and height of the mercury column 67.4 cm. A mechanical drop time of 1.000 s was maintained during all experiments. Oxygen was expelled by bubbling with CH_3CN-saturated, deoxygenated (copper scraps, 600 °C) nitrogen

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(39) *Structure Determination Package*; B. A. Frenz and Associates Inc.; College Station, TX, and Enraf-Nonius, Delft, 1983.
(40) Dupuis, M.; Spangler, D.; Wendoloski, J. J. NRCC Software Catalog, Vol. 1, Program N. QG01 (GAMESS), 1980; Guest, M. F.; Kendrick, J. GAMESS Users Manual, Daresbury Laboratory, 1985.
(41) Dewar, M. J. S.; Zoebisch, E. G.; Healy, E. F.; Stewart, J. J. P. *J. Am. Chem. Soc.* **1985**, *107*, 3902.
(42) Available as program 506 QCPE, Department of Chemistry, Indiana University, Bloomington, IN 47405.

(Hoek Loos, very pure) for at least 20 min. The sample starting concentrations were 0.3–1.0 mM of host. After each manual addition (Hamilton syringes with a total volume of 50 μL or 250 μL were used) of guest (0.25–5.0 equiv from 50–500 mM in 0.1 M solutions of $Et_4N^+ClO_4^-$ in CH_3CN), polarograms were recorded in triplicate in the DC-tast mode with scan speed of 5 mV/s. The number of additions was 5–8. The values of half-wave potential, limiting current and slope of the log plot, were calculated by a computerized curve-fitting method described by Zollinger et al.[29] Stability constants were obtained from the polarographic data (half-wave potential and limiting current) with POLAG[30] using least-squares fitting procedures. The error between experimental and calculated values for the half-wave potentials were <1 mV; to achieve this accuracy deviations in the slope must be <3 mV. Estimated accuracy of the association constants is 20%.

Cyclic voltammetry was carried out with a AUTOLAB-computerized system for electrochemistry (ECO CHEMIE, Utrecht, The Netherlands). The measurements were performed at a stationary hanging mercury drop electrode (Metrohm, 663 VA) with a scan rate of 4–6 V/s in the range −0.7/−1.3 V. The electrode types and fillings were the same as used in polarography. The solvent and the supporting electrolyte were also the same as used in polarography. Oxygen was expelled by bubbling CH_3CN-saturated nitrogen (Hoek Loos, very pure) through for at least 5 min.

Coulometry was carried out with a Metrohm coulostat E524 and a Metrohm integrator E525. The coulostat was operated with a constant potential (potentiostatic coulometry) of −1.3 V. The electrode types and fillings were the same as used in polarography. The solvent and the supporting electrolyte were also the same as used in polarography and cyclic voltammetry. A mercury pool was used as cathode and it was separated from the platinum counter electrode by a salt bridge. Oxygen was expelled by bubbling CH_3CN-saturated nitrogen (Hoek Loos, very pure) through for at least 10 min.

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Supplementary Material Available: Tables of positional and thermal parameters of all non-hydrogen atoms, bond distances and angles, and dihedral angles of the compounds **1**(n=5)·MeOH, **6b**·urea, and **6d**·urea, and 2D COSY spectra of **5b** and **6b**·urea and a 2D NOESY spectrum of **5b** (23 pages). Ordering information is given on any current masthead page.

Synthesis of the Bicyclo[3.2.0] Ring Systems from 4-Allylcyclobutenones. Intramolecular Ketene/Alkene Cycloadditions

Simon L. Xu, Haiji Xia, and Harold W. Moore*

Department of Chemistry, University of California, Irvine, California 92717

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A general synthesis of bicyclo[3.2.0]heptenones from 4-allylcyclobutenones is described. The rearrangement is envisaged to involve an electrocyclic ring opening of the cyclobutenone and subsequent intramolecular 2 + 2 cycloaddition of the resulting vinylketene to the nonconjugated allylic alkene moiety. This method is particularly suitable for the synthesis of highly substituted derivatives since the regiochemistry of the substitution pattern is conveniently controlled. The scope of the rearrangement and the mechanism are discussed.

Introduction

Intermolecular ketene/alkene cycloadditions have received detailed attention.[1,2] In view of this it is surprising that the intramolecular versions have received much less study. However, those reports that have appeared point to a potentially powerful method for the synthetic arsenal.[3] In this conjunction we now provide the details of a study focussing on the generation of vinylketenes from 4-allylcyclobutenones and their intramolecular cycloadditions to tethered alkenes, thus providing highly functionalized bicyclo[3.2.0]heptenone derivatives.

Most systematic studies of intramolecular ketene/alkene cycloadditions and their applications in the synthesis of complex natural products have appeared during the past decade.[4] In general, these report the ketene syntheses by standard methods including the elimination of HCl from the corresponding acid halide and/or the pyrolysis of esters, the photo-Wolff rearrangement of diazo ketones, and, to a less extent, the electrocyclic ring opening of a cyclobutenone.[5-7] In general, intramolecular ketene/al-

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