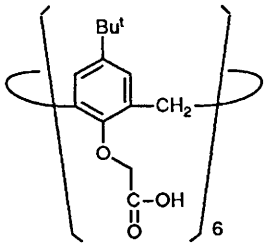
Synthesis and Solvent Extraction Properties of a Novel Calixarene-based Uranophile Bearing Hydroxamate Groups

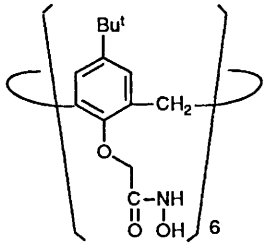
Takeshi Nagasaki, Seji Shinkai,* and Tsutomu Matsuda
Department of Organic Synthesis, Faculty of Engineering, Kyushu University, Fukuoka 812, Japan

A *p*-t-butylcalix[6]arene derivative bearing six hydroxamate groups has been synthesized: it efficiently extracted UO_2^{2+} from the aqueous phase to the organic phase.

The selective extraction of uranium has attracted extensive attention from chemists because of its importance in relation to energy problems. We previously found that a hexacarboxylate derivative of *p*-t-butylcalix[6]arene (**1**) can extract uranyl ion (UO_2^{2+}) efficiently and selectively from water into organic media.[1,2] The high selectivity was attributed to the basic skeleton of calix[6]arene: this has a skeleton suitably structured for the binding of UO_2^{2+} which requires a pseudo-planar hexaco-ordination.[3] Meanwhile, it has been established in a polymer chemistry field that the hydroxamate group acts as an efficient ligand for adsorbing UO_2^{2+} on a chelate resin.[4,5] This tempted us to synthesize a new uranophile (**2**) bearing six hydroxamate groups on a calix[6]arene ring. In this communication we report the synthesis and extraction properties of (**2**).

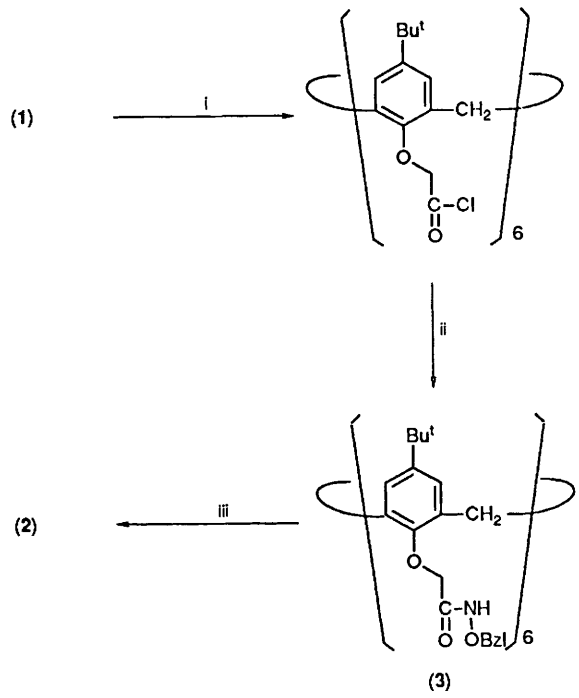


(1)



(2)

Calixarene (**2**) was synthesized from (**1**) *via* the acid chloride (see Scheme), the product being identified on the basis of IR and NMR spectral evidence and elemental analysis.† The concentration of UO_2^{2+} extracted into the organic phase was calculated from the analysis of UO_2^{2+} remaining in the aqueous phase, using Arsenazo III.[6] The details of the extraction conditions are recorded in the captions to Figures 1 and 2.‡



Scheme. *Reagents:* i, $(COCl)_2$; ii, *O*-Benzylhydroxylamine; iii, H_2/Pd–C.

Figure 1 shows the extractability (Ex%) of UO_2^{2+} plotted against pH in the aqueous phase. The Ex% for (**1**) increases from pH 2 and is saturated at around pH 5 showing the 100% extractability. This pH dependence is apparently correlated with the dissociation of the carboxy groups (*e.g.*, phenoxyacetic acid has $pK_a = 3.12$ in water).[7] The Ex% for (**2**) shows a similar pH dependence although the pH 'jump' is slightly shifted to higher pH region. The pK_a values for hydroxamic acids are 8–9.[7] Thus, the pH 'jump' for (**2**) appears at an unusually low pH region, indicating that the dissociation of the hydroxamic groups in (**2**) is markedly facilitated by the binding to UO_2^{2+}.

The plots of log *D* (distribution ratio = $[UO_2^{2+}]$ in the organic phase/$[UO_2^{2+}]$ in the aqueous phase) *vs.* pH at pH 3.0–4.5 showed a slope of unity for (**1**). This implies that one carboxy group is dissociated upon extraction of UO_2^{2+} (data not shown here). On the other hand, the plot for (**2**) gave a slope of 2, indicating the dissociation of two hydroxamic groups upon extraction of UO_2^{2+}. To clarify this difference we repeated the extraction experiments in the absence of UO_2^{2+} ion. The organic layer was separated and then re-extracted with aqueous 0.1M HCl. The analysis of the aqueous solution by atomic absorption spectrophotometry established that at pH 3.0–4.5 the K^+ ion is not extracted at all with (**2**) whereas (**1**) does extract K^+, the concentration being always equal to that of

† European Patent No. 0237265 describes the synthesis of ester and amide derivatives of calixarenes *via* the acid chlorides. It is very difficult, however, to synthesize fully-substituted calixarenes from the acid chlorides. We could overcome this problem by using carefully dehydrated CCl_4 as solvent and a high reaction temperature (reflux in CCl_4), and we applied the method to the synthesis of a fully-substituted hydroxamate derivative. *Compound* (**3**): yield [from (**1**)] 36%, m.p. 212–215 °C; ν_{max}(Nujol) 1 680 (C=O) and 3 220 (NH) cm^{-1}; $\delta_H[(CD_3)_2SO$; 150 °C] 1.02 (9 H, s, Bu^t), 3.97 (2 H, br, $ArCH_2Ar$), 4.33 (2 H, s, OCH_2), 4.85 (2 H, s, $PhCH_2$), 7.01 (2 H, s, ArH in calixarene), 7.23–7.34 (5 H, m, ArH in benzyl) [Found: C, 73.95; H, 7.1; N, 4.3. $(C_{20}H_{23}NO_3)_6$ requires C, 73.82; H, 7.12; N, 4.30%]. *Compound* (**2**): yield 80% m.p. (decomp.) 207 °C; ν_{max}(Nujol) 1 660 (C=O) and 2 500–3 600 (OH and NH) cm^{-1}; $\delta_H[(CD_3)_2SO$; 150 °C] 0.79–1.37 (9 H, m, Bu^t), 3.34–3.85 (2 H, m, $ArCH_2Ar$), 4.25 (2 H, s, OCH_2), 6.48–7.65 (2 H, m, ArH) [Found: C, 66.05; H, 7.15; N, 5.5. $(C_{13}H_{17}NO_3)_6$·EtOH (recrystallized from hexane–EtOH) requires C, 65.96; H, 7.40; N, 5.76%].

‡ The ^1H NMR spectrum of (**2**) under the extraction conditions ($CDCl_3$; 30 °C) gave a broad singlet at 3.66 ppm. This indicates that (**2**) retains a conformational freedom.

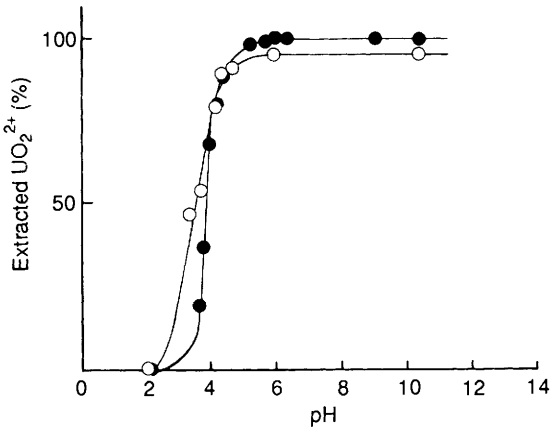


Figure 1. pH Dependence for UO_2^{2+} extraction from water (25 ml) to chloroform (5 ml) at 30 °C; [**1**(○) or **2**(●)] = 5.30×10^{-4}M, $[K_4UO_2(CO_3)_3] = 1.06 \times 10^{-4}$M. The aqueous phase was buffered with 10 mM acetate (pH 3.7–6.2), Tris (pH 9.0), and ammonia (pH 10.4).

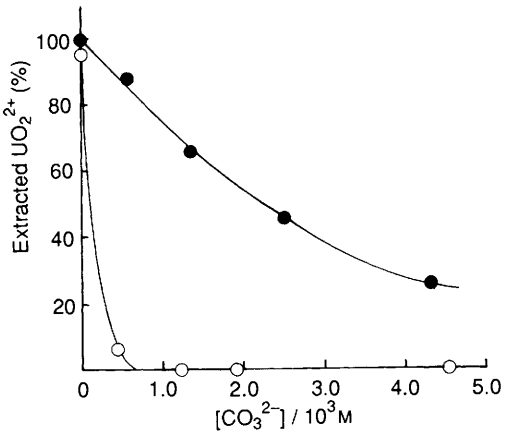


Figure 2. UO_2^{2+} Extraction from carbonate buffer solution at 30 °C. [**1**(○) or **2**(●)] = 5.30×10^{-4}M, $[K_4UO_2(CO_3)_3] = 1.06 \times 10^{-5}$M. The solution pH was maintained at 10.4. At $[CO_3^{2-}] = 0$, $UO_2(CH_3COO)_2$ was used instead of $K_4UO_2(CO_3)_3$ and the solution was buffered with 10 mM ammonia.

UO_2^{2+} observed in the presence of UO_2^{2+}. These findings support the extraction mechanisms in equations (1) and (2)

$$[(\mathbf{1})H_5^- \cdot K^+]_{org} + (UO_2^{2+})_{aq} \rightleftharpoons [(\mathbf{1})H_4^{2-} \cdot UO_2^{2+}]_{org} + (H^+)_{aq} + (K^+)_{aq} \quad (1)$$

$$[(\mathbf{2})H_6]_{org} + (UO_2^{2+})_{aq} \rightleftharpoons [(\mathbf{2})H_4^{2-} \cdot UO_2^{2+}]_{org} + 2(H^+)_{aq} \quad (2)$$

[(**1**)H_6 and (**2**)H_6 denote the undissociated species of (**1**) and (**2**), respectively, and 'org' and 'aq' denote the species present in the organic phase and in the aqueous phase]. The mechanisms are also in line with the high affinity of (**2**) towards UO_2^{2+}.

In order to compare the UO_2^{2+} affinity we carried out two-phase solvent extraction under more severe conditions. It is known that carbonate ions form a stable, water-soluble complex $UO_2(CO_3)_3^{4-}$ with UO_2^{2+}.[8] We determined Ex% as a function of the carbonate concentration (Figure 2). The Ex% for (**1**) was reduced to 5.7% at $[CO_3^{2-}] = 4.27 \times 10^{-4}$M and 0% at 1.22×10^{-3}M. In extraction with (**2**), in contrast, Ex% was 87.9% at $[CO_3^{2-}] = 5.92 \times 10^{-4}$M and 26.1% was still retained even at $[CO_3^{2-}] = 4.33 \times 10^{-3}$M. This implies that (**2**) can sufficiently compete with CO_3^{2-} ions for UO_2^{2+}.

The foregoing results consistently indicate the superiority of the hydroxamate uranophile (**2**) over the carboxylate uranophile (**1**). The significant improvement in the UO_2^{2+} affinity is ascribed to the high affinity of hydroxamate groups with UO_2^{2+}, which has already been demonstrated by chelate resins.[4,5] Also important is the skeleton of calix[6]arene, we believe, that can arrange hydroxamate groups in such a way suitable to the binding to UO_2^{2+}, *i.e.* in a hexaco-ordinated geometry.

Acknowledgements

This research was supported by a grant from the Ministry of Education of Japan.

References

1 S. Shinkai, Y. Shirahama, H. Satoh, O. Manabe, T. Arimura, K. Fujimoto, and T. Matsuda, *J. Chem. Soc., Perkin Trans. 2*, 1989, 1167.
2 The similar idea using macrocyclic uranophiles was reported by Kobuke *et al.*; Y. Kobuke, I. Tabushi, K. Oh, and T. Aoki, *J. Org. Chem.*, 1988, **43**, 5933.
3 S. Shinkai, H. Koreishi, K. Ueda, T. Arimura, and O. Manabe, *J. Am. Chem. Soc.*, 1987, **109**, 6371.
4 H. Egawa, T. Nonaka, and M. Ikari, *J. Appl. Polym. Sci.*, 1984, **29**, 2045.
5 For a comprehensive review see H. Egawa, *Nippon Kaisui Gakkaishi* 1988, **41**, 235.
6 H. Ohnishi and Y. Higashi, *Bunseki Kagaku*, 1965, **14**, 1141.
7 W. P. Jencks and J. Regenstein, 'Handbook of Biochemistry and Molecular Biology,' ed. G. D. Fasman, CRC Press, 1976, p. 305.
8 S. O. Cinneide, J. P. Scanlan, and M. J. Hynes, *J. Inorg. Nucl. Chem.*, 1976, **37**, 1013.

Paper 0/01849J
Received 25*th April* 1990
Accepted 26*th June* 1990