



Journal of Applied Sciences

ISSN 1812-5654

science
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Synthesis under Microwave Irradiation, Characterization and Application of Alkyliminodimethylenediphosphonic Acids in Solvent Extraction of Uranium (VI)

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Abstract: The synthesis under microwave irradiation, characterization and application of new alkyliminodimethylenediphosphonic acids in solvent extraction of uranium (VI) have been investigated. The alkyliminodimethylenediphosphonic acids synthesized were: hexadecyliminodimethylenediphosphonic acid (HIDMP, H_4L^1) and decyliminodimethylenediphosphonic acid (DIDMP, H_4L^2). After purification, these products were characterized by elemental analysis and by FT-IR, 1H NMR, ^{13}C NMR, ^{31}P NMR spectroscopy. In this study, we propose a tentative assignment for the shifts of those two ligands and their specific complexes with uranium (VI). We also carried out the extraction of uranium (VI) by HIDMP and DIDMP from [chloroform+2-octanol (v/v: 90/10%)] solutions at an aqueous to organic phase ratio (1/1) and at room temperature. Experimental results showed that The HIDMP and DIDMP are synthesised efficiently and rapidly in good yields (85-88%) under microwave irradiation. The extraction yields are more significant in the case of the HIDMP (98%) which is equipped with a hydrocarbon chain, longer than that of the DIDMP (94%). Logarithmic plots of the uranium (VI) distribution ratio vs. pH_{eq} and the extractant concentration showed that the ratios of extractant to extracted iron (III) is 2:1. The metal complexes formed in organic phase are $[UO_2(H_3L^1)_2 \cdot 2H_2O]$ and $[UO_2(H_3L^2)_2 \cdot 2H_2O]$ with HIDMP and DIDMP, respectively. A spectroscopic analysis of the metal complexes has showed that coordination of uranium (VI) takes place via oxygen atoms in the phosphonic groups, whereas the nitrogen atom remains rather uncoordinated. The equilibrium constants for the extraction of uranium (VI) were found to be 10.45×10^{-3} and 2×10^{-3} for HIDMP and DIDMP, respectively.

Key words: Synthesis, microwave irradiation, alkyliminodimethylenediphosphonic acids, extraction, uranium

INTRODUCTION

Aminophosphonic acids, synthesized for the first time in 1945 by Schwarzenbach *et al.* (1949), Matczak-Jon *et al.* (1999) and Naydenova *et al.* (2010). These acids are very good ligands for the coordination of metal ions so they can be used for the extraction of metals such as uranium, iron, copper and nickel in hydrometallurgy (Villemin *et al.*, 2008; Naydenova *et al.*, 2010; Matczak-Jon *et al.*, 1999; Abderrahim *et al.*, 2006; Belkhouche *et al.*, 2006; Didi *et al.*, 2004; Sawaji *et al.*, 1992; Turner *et al.*, 2003; Nowack, 2002; Rao, 2010). Aminophosphonic acids are also used as insecticides, herbicides, bactericides, plant-growth regulators, enzyme inhibitors, anticancer agents, etc. (Naydenova *et al.*, 2010; Kukhar and Hudson, 2000; Matczak-Jon *et al.*, 1999;

Juribasic *et al.*, 2009; Kurzak *et al.*, 2000; Kafarski and Lejczak, 2000; Kafarski and Lejczak, 2001; Sun *et al.*, 2003; Ying and Mao, 2005; Lebouc *et al.*, 2005; Yoshikawa, 1995; Redmore, 1972).

Aminophosphonic acids are generally obtained by hydrolysis of esters via Kabachnik-Fields reaction (Kabachnik and Medved, 1952; Fields, 1952; Moedritzer and Irani, 1966; Villemin *et al.*, 2008; Naydenova *et al.*, 2010). This reaction can be activated by microwave irradiation; nevertheless there are often secondary reactions during the hydrolysis (Villemin *et al.*, 2008; Naydenova *et al.*, 2010; Juribasic *et al.*, 2009). The synthesis of Irani-Moedritzer is less general than the Kabachnik-Fields reaction, but it has the advantage of obtaining the aminophosphonic acids without a step of hydrolysis (Moedritzer and Irani, 1966). The

Irani-Moedritzer reaction times are in general long, so the use of microwave for assisting the reaction is of interest (Villemin *et al.*, 2008; Naydenova *et al.*, 2010). This reaction is carried out in aqueous medium under microwave irradiation with an aqueous solution of formaldehyde in acidic aqueous medium without organic solvent. Water is an inexpensive, non flammable, non toxic solvent and has the advantage of warming up quickly under microwave irradiations. Carrying out reactions using microwave heating, as opposed to conventional heating, has the major advantage of shorter reaction times because of the rapid heating (Villemin *et al.*, 2008; Lidstrom and Tierney, 2005; Loupy, 2006). The Irani-Modzdrizer reaction can be compared to a Mannich reaction and takes place by the addition of the phosphorous acid on iminium salt formed by reaction of formaldehyde with the amine in acidic medium (Moedritzer and Irani, 1966).

In this study, we describe the synthesis two new alkyliminodimethylenediphosphonic acids under microwave irradiation. The synthesis of the iminodimethylenediphosphonic acids under microwaves irradiation is fast and efficient than a conventional heating (Didi *et al.*, 2007; Simeon, 1998; Villemin *et al.*, 2008; Naydenova *et al.*, 2010). These acids exhibited high complexation efficiency towards zinc (II), magnesium (II), calcium (II) and nickel (II) ions. This results from both dinegatively charged phosphonate groups as well as the imino-nitrogen present in their structure (Maczak-Jon *et al.*, 1999; Didi *et al.*, 2007; Naydenova *et al.*, 2010). In fact, we have synthesized hexadecyliminodimethylenediphosphonic acid, $C_{16}H_{33}N(CH_2PO_3H_2)_2$ (HIDMP, H_4L^1), and decyliminodimethylenediphosphonic acid, $C_{10}H_{21}N(CH_2PO_3H_2)_2$ (DIDMP, H_4L^1) for such a purpose. The characterizations of these products were carried out by elemental analyse and by FT-IR, 1H NMR, ^{13}C NMR, ^{31}P NMR spectroscopy. We have also tested the chelating properties of these extractants towards uranium (VI).

MATERIALS AND METHODS

This research project was conducted from April 2009 to June 2010 in the Nuclear Research Center of Draria, Algiers, Algeria.

Reagents and solutions: The reagents used in this study were 1-hexadecylamine (90 %, Alfa), 1-decylamine (95%, Merck), phosphorous acid (99%, Aldrich), formaldehyde (37.5%, Panreac), hydrochloric acid (36%, Merck) and uranyl nitrate hexahydrate (99%, Merck). Chloroform (Merck) and 2-octanol (Prolabo) of analytical grade were

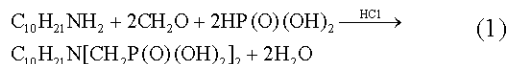
used without further purification. The aqueous solutions of 0.015 M uranium (VI) was prepared from uranyl nitrate hexahydrate and adjusted at pH 2 with nitric acid and NaOH. The aqueous solutions of uranium (VI) was fixed at pH 2, because hydrolysis of uranyl ion takes place as the pH varies from 1 to 3.0 ± 0.1 (availability of free uranium ions). When pH increases beyond 3.0 ± 0.1 , uranium exists in hydrolyzed form and the following ionic species have been identified: UO_2^{2+} , $[(UO_2)_2(OH)_2]^{2+}$ dimer, $[(UO_2)_3(OH)_5]^+$ trimer, precipitation starts due to the formation of complexes in aqueous solution (Kadous *et al.*, 2009). The organic solutions were prepared from of HIDMP and DIDMP (0.03 to 0.3 M) dissolved in the organic solvent (chloroform+2-octanol (v/v: 90%/10%)).

Instrumentation: The microwave experiments were conducted in Synthewave 402 microwave oven supplied from Prolabo. This microwave oven fitted monomode resonance cavity TE_{013} at 2450 MHz working with 800 W max and equipped with a universal generator MES 73-800 (Micro-ondes Energie Systèmes 2). ^{13}C $\{-^1H\}$, ^{31}P $\{-^1H\}$ and 1H -NMR spectra were measured on Bruker AC 250 working at 250 MHz in $CDCl_3$ solution. Infrared spectra were measured on a Perkin Elmer 16 PC-FTIR equipped with a thermostat to maintain the temperature of the sample cell at $25 \pm 0.1^\circ C$. Elemental analyses were performed using a ThermoQuest NA2500 elemental analyser. pH measurement were taken on a potentiometer Consort C 831 with combined glass electrode was used to measure the pH of the aqueous solution before and after extraction. In a water-acetone mixture (5:15) a known mass of each sample titrated by a solution of NaOH ($5 \times 10^{-4} M$). Metal ion was determined using the atomic absorption spectrophotometer, system GBC Avanta. Water was titrated in the organic phase by the use of a Mettler DL18 Karl Fisher Titrator.

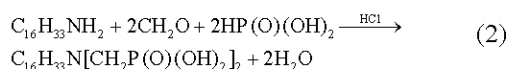
Synthesis of the extractants: HIDMP and DIDMP were prepared by a Mannich type reaction according to the procedures previously described (Moedritzer and Irani, 1966; Didi *et al.*, 2007; Simeon, 1998; Villemin *et al.*, 2008; Naydenova *et al.*, 2010; Turner *et al.*, 2003; Yoshikawa, 1995).

A mixture of phosphorous acid (1.64 g, 20 mmol), water (2 mL) and hydrochloric acid (2 mL) was added to a 2 mL 1-decylamine (10 mmol) placed in a tube made of quartz. The mixture is irradiated for 5 min at 240 W. Three milliliter formaldehyde (40 mmol) were then added quickly and the assembly is irradiated at 400 W for 8 min. The product precipitated directly into the tube, then it is filtered, then washed with acetone and rinsed with water.

The product was obtained as white solid. Its melting point is 248°C. The yield is 88%. The reaction of the synthesis is of the following form:



The procedure above was analogously repeated using 2.144 g (10 mmol) of 1-hexadecylamine. The product was obtained as white solid. Its melting point is 214°C. The yield is 85%. The reaction of the synthesis is of the following form:



Extraction experiments: The extraction tests were performed using HIDMP and DIDMP as extracting agents. These substances were tested for uranium (VI) extraction from aqueous solutions at pH 2. Equal volumes of organic and aqueous phases (10 mL) were shaken together at 25°C for 15 min. Preliminary experiments showed that equilibration was complete in 15 min (Didi *et al.*, 2002). The addition of 2-octanol in organic solution as modifier (10 vol.%) was necessary to improve phase separation. This alcohol also prevents micelle formation and solvated metal-extractant complexes (Didi *et al.*, 2002; Kahlweit *et al.*, 1991; Strey and Jonstromer, 1992; Mellah and Benachour, 2006). It is very important to note

that no third phase or any precipitation was observed during the extraction process. After shaking, the organic phase was separated from the aqueous phase. The amount of uranium (VI) extracted was determined by complexing the uranium (VI) in the aqueous phase before and after extraction with arsenazo III and by further visible spectrophotometric dosage of the complexes formed (Elias *et al.*, 1996; Marczenko, 1976). The metal ion concentration in the organic phase was calculated from the difference between the metal ion concentrations in the aqueous phase before and after extraction. The water was titrated in the organic phase by the use of a Karl Fisher Titrator.

RESULTS AND DISCUSSION

Analysis and characterisation of HIDMP and DIDMP: The results showed that The HIDMP and DIDMP are synthesised efficiently and rapidly in good yields (85-88%) under microwave irradiation (Didi *et al.*, 2007; Simeon, 1998; Villemin *et al.*, 2008; Naydenova *et al.*, 2010). The structure of the complexing agents synthesis were identified and characterized by elemental analyse and by FT-IR, ¹H NMR, ¹³C NMR, ³¹P NMR spectroscopy (Table 1).

HIDMP and DIDMP were titrated by potentiometry. The measurements indicated that, in the water-acetone medium these acids probably exist as zwitterions with three titratable protons, a strongly dissociated proton and

Table 1: HIDMP and DIDMP characteristics

Products	HIDMP				DIDMP			
Formula	C ₁₆ H ₃₃ N (CH ₂ PO ₃ H ₂) ₂				C ₁₀ H ₂₁ N (CH ₂ PO ₃ H ₂) ₂			
pKa	3.2, 6.5, 8.64±0.05				3.7, 6.87, 8.8±0.05			
Elemental analysis		%C	%H	%N		%C	%H	%N
	Exptl.	50.43	9.88	6.40	Exptl.	41.25	8.61	6.40
	Calcd	50.34	9.62	6.17	Calcd	41.73	8.49	6.17
¹ H NMR δ (ppm)	0.85 (t, 3H, (CH ₃)),				0.85 (t, 3H, (CH ₃)),			
	1.38 (m, 26H, (CH ₂)),				1.24 (m, 14H, (CH ₂)),			
	1.83 (d, 2H, (- ^β CH ₂ -)),				1.75 (d, 2H, (^β CH ₂)),			
	3.06 (t, 2H, (- ^α CH ₂ -N)),				3.40 (t, 2H, (- ^α CH ₂ -N)),			
	3.21 (t, 2H, (N-CH ₂ -P)),				3.39 (d, 2H, (N-CH ₂ -P)),			
¹³ C NMR (δ ppm)	4.89 (d, 4H, (P(O)(OH) ₂))				4.10 (d, 4H, (P(O)(OH) ₂)),			
	14.80 (s, (CH ₃)),				14.0 (s, (CH ₃)),			
	22.90 and 32.10 (14s, (CH ₂)),				22.1 and 31.3 (8s, (CH ₂)),			
	53.80 (s, (CH ₂ -N)),				53.5 (s, (CH ₂ -N)),			
	52 (d, J _{CP} = 142.1, (N-CH ₂ -P))				51.2 (d, J _{CP} = 41.3, (N-CH ₂ -P))			
³¹ P NMR δ (ppm)	+6.08 (s)				+5.57 (s)			
FT-IR (cm ⁻¹)	2928 (vs CH),				2924 (vs CH),			
	2858 (vs CH),				2854 (vs CH),			
	2750-2550 and 2380-2100 (vs POH),				2770-2570 and 2364-2084 (vs PO-H),			
	1650-1520 (vs N-CH ₂),				1648-1518 (vs N-CH ₂),			
	1463 (δ CH),				1462 (δ CH),			
	1180 (vs P = O),				1168 (vs P = O),			
	945 (vs P-OH),				942 (vs P-OH),			
	716 (vs N-CH ₂ -P)				712 (vs N-CH ₂ -P)			

Exptl. and calcd: Experimental and calculated percentages for the elemental analysis of the synthesized compounds, δ (ppm): chemical shift, s: Singlet, d: Doublet, t: triplet, m: Multiplet, vs: symmetric stretching, vas: Antisymmetric stretching

two weak ones, with the fourth available proton being coordinated to the central nitrogen atom (Moedritzer and Irani, 1966).

The displacement of $\nu_P = O$ to lower frequency in the infrared spectra indicates the existence of intermolecular hydrogen bonds $P = O \dots H-OP$. The band appearing between $1650-1520 \text{ cm}^{-1}$ indicates the existence of bond $N \dots H$ intermolecular of $N \dots H-O-P$.

Extraction of uranium (VI) by HIDMP and DIDMP: The extraction experiments results are discussed in term of extraction yield (Y) and distribution ratio (D) defined as follows:

$$Y (\%) = \frac{m_i - m_f}{m_i} \times 100 \quad (3)$$

$$D = \left(\frac{m_i - m_f}{m_f} \right) \times \frac{V_{aq}}{V_{org}} \quad (4)$$

where, m_i is initial mass of uranium (VI) in aqueous phase; m_f is mass of uranium (VI) after extraction; V_{aq} is the volume of the aqueous phase; V_{org} is the volume of the organic phase.

The variable Q is the ratio of the number of moles of extractant in organic phase versus the number of moles of metal in aqueous phase before extraction.

$$Q = \frac{n_{extractant}}{n_{metal}} \quad (5)$$

The variation of the extraction yield test of 0.015 M uranium (VI) from aqueous solutions as a function of Q is shown in Fig. 1.

Figure 1 shows the yield of extraction of uranium (VI) increases with Q. Working with extractants

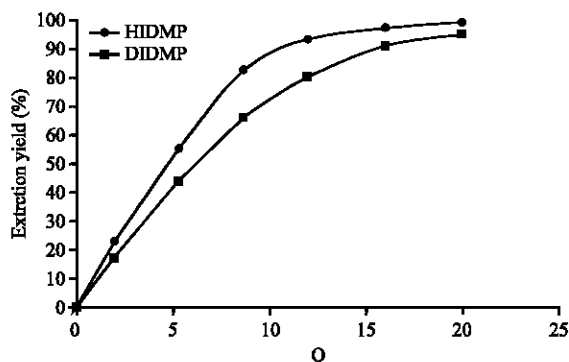
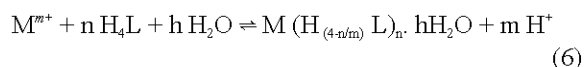


Fig. 1: Effect of the molar ratio on the extraction yield of uranium (VI). $[U(VI)] = 0.015 \text{ M}$, $V_{aq}/V_{org} = 1$, $t = 25 \text{ }^\circ\text{C}$

concentrations range 0.03 to 0.3 M ($Q = 2$ to 20), we reached a yield of 98% for HIDMP and 94% for DIDMP. The extractant with a longer alkyl group forms more hydrophobic complexes. HIDMP and DIDMP present a similar extraction power, but the hydrophobic character determines the amount of extraction. The hydrophobic character of ligand can be determined calculating log P which is defined as the partition coefficient between two phases of a substance, generally n-octanol and water. Modern molecular modeling software allows the log P values, calculated using ChemDraw Ultra (Cambridge Soft) are, respectively 1.16 for DIDMP and 5.93 for HIDMP showing that HIDMP is strongly hydrophobic (Didi *et al.*, 2002, 2008).

Stoichiometry of extracted species: In the work on stoichiometric relation for the extraction of iron complex with HIDMP (H_4L^1) and DIDMP (H_4L^2), we have supposed that the solubilities of the extractant and the uranium-extractant complex in the aqueous phase are negligible; the overall reaction in the extraction of metal cations by cationic extractants, as the case of HIDMP and DIDMP, can be show as following:



where, H_4L is the molecule of extractant, M is the metal (U), m valency of metal (U(VI)), n molecules of extractant engaged in the reaction, n/m number of protons exchanged by each extractant and h number of molecules of water.

The equilibrium constant of the above reaction, K_{ex} , can be given as function of molar concentration:

$$K_{ex} = \frac{[M(H_{(4-n/m)}L)_n \cdot hH_2O] [H^+]^m}{[M^{m+}] [H_4L]^n} \quad (7)$$

Substitution of the distribution ratio, which is defined by the concentration of metal in organic phase divided by that in aqueous phase, into Eq. 8 results in:

$$D = \frac{K_{ex} [H_4L]^n}{[H^+]^m} \quad (8)$$

Taking logarithms of Eq. 8, one obtains:

$$\log D = \log K_{ex} + n \log [H_4L] - m \log [H^+] \quad (9)$$

$$\log D = \log K_{ex} + n \log [H_4L] + m \text{pH} \quad (10)$$

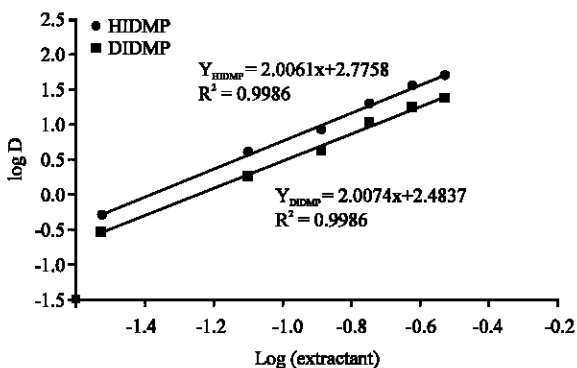


Fig. 2: Effect of extractant concentration on the distribution ratio for uranium (VI). [U (VI)] = 0.015 M, $V_{aq}/V_{org} = 1$, $t = 25^\circ\text{C}$

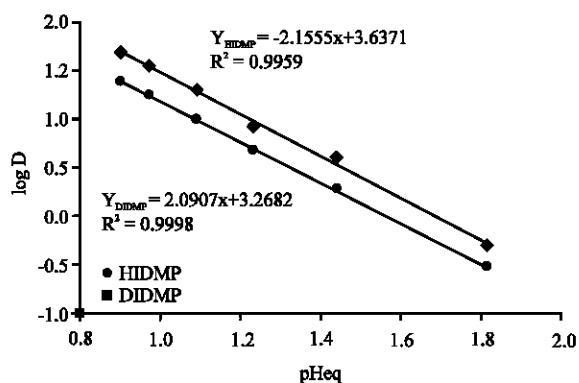


Fig. 3: Effect of equilibrium pH on the distribution ratio for uranium(VI). [U (VI)] = 0.015 M, $V_{aq}/V_{org} = 1$, $t = 25^\circ\text{C}$

The stoichiometry of the extracted species was determined by analysing the experimental data. The conventional slope analyses method was used. Figure 2 shows the plots of log D versus log [extractant] which gave two straight lines with good correlation coefficients 0.998 and slopes equal to 2 for HIDMP and DIDMP. This result suggests that two molecules of extractant react with one uranyl ion (UO_2^{2+}). Figure 2 also shows that the distribution ratio of uranium (VI) increases with the increase in extractant concentration. The distribution ratios are more significant in the case of the HIDMP which is equipped with a hydrocarbon chain, longer than that of the DIDMP. Figure 3 shows the plots of log D versus pH_{eq} which also gave two straight lines with good correlation coefficients 0.996 and 0.999 and slopes equal to 2.15, which is close to 2 and 2.09, which is close to 2 for HIDMP and DIDMP, respectively. This indicates that two protons are released during the cation exchange reaction. The plots log D versus log [extractant] and the plots log

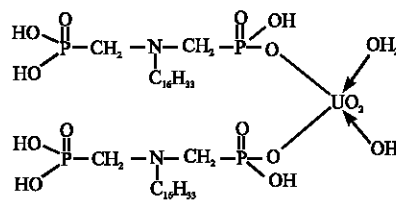


Fig. 4: Structure of the complex HIDMP-Fe(III). $3\text{H}_2\text{O}$

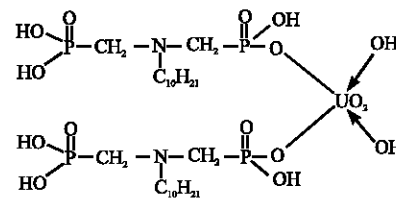
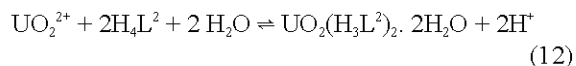
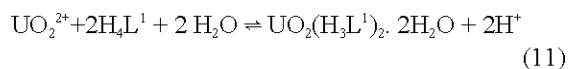


Fig. 5: Structure of the complex DIDMP- UO_2 . $2\text{H}_2\text{O}$

D versus pH_{eq} suggest that the ratio of extractant to extracted uranium (VI) is 2:1 (Songling *et al.*, 1993; Kong *et al.*, 2004; Sun *et al.*, 2003; Kurzak *et al.*, 2000; Rao, 2010). The equations extraction equilibrium can thus be written as:



According to the above equations extraction equilibrium, The metal complexes formed in organic phase are $[\text{UO}_2(\text{H}_3\text{L}^1)_2 \cdot 2\text{H}_2\text{O}]$ and $[\text{UO}_2(\text{H}_3\text{L}^2)_2 \cdot 2\text{H}_2\text{O}]$ for HIDMP and DIDMP, respectively (Songling *et al.*, 1993; Sun *et al.*, 2003; Kurzak *et al.*, 2000). Protons, intervening in our extraction, correspond to the pK_a of HIDMP and DIDMP, 3.2 and 3.7, respectively. HIDMP and DIDMP extract the uranyl ions in cationic exchange mode. The two last values of pK_a obtained by potentiometric measurement confirm that the extracting agent can exchange only one or two protons per molecule. We also note that the extraction of uranium (VI) by HIDMP and DIDMP is accompanied by two water molecules extraction. The equilibrium constants for the extraction of uranium (VI) were found to be 10.45×10^{-3} and 2×10^{-3} for HIDMP and DIDMP, respectively.

The structures of the complex HIDMP- $\text{UO}_2 \cdot 2\text{H}_2\text{O}$ and DIDMP- $\text{UO}_2 \cdot 2\text{H}_2\text{O}$ are indicated in Fig. 4 and 5.

Figure 4 and 5 show that the uranium complexes, $[\text{UO}_2(\text{H}_3\text{L}^1)_2 \cdot 2\text{H}_2\text{O}]$ and $[\text{UO}_2(\text{H}_3\text{L}^2)_2 \cdot 2\text{H}_2\text{O}]$, are formed by coordinating of each uranyl ion to two phosphonate oxygen atoms from two molecules of extractant agent. The

Fig. 4 and 5 show also that these complexes contain two water molecules. The HIDMP and DIDMP exhibited high complexation efficiency towards uranyl ions. This results from both dinegatively charged phosphonate groups as well as the imino-nitrogen and the hydrophobic character present in their structure (Matczak-Jon *et al.*, 1999; Naydenova *et al.*, 2010; Kabachnik *et al.*, 1974, 1975; Van Hecke and Goethals, 2006; Sun *et al.*, 2003).

HIDMP-UO₂ and DIDMP-UO₂ spectra: The solid complex HIDMP-UO₂ was prepared by stirring the iminodimethylenediphosphonic acid in the organic solvent mixture (chloroform +2-octanol), with an aqueous solution of uranium (VI). After separation of the phases and evaporation of the organic solvents, the solid complex was washed with water and dried. We have observed a shift of P = O band from 1180 to 1091 cm⁻¹. In the complex, a new IR band appears at 940 cm⁻¹ attributed to the distortion vibration PO-UO₂. Similarly, comparison of the spectra of DIDMP and DIDMP-UO₂ show a shift the 1168 P = O band to 1070 cm⁻¹. A new band in DIDMP-UO₂ appears at 933 cm⁻¹ attributed to the deformation vibration of PO-UO₂. The two deformation vibrations PO-UO₂ showed that the bond between P-O and UO₂ for HIDMP is stronger than with DIDMP. A spectroscopic analysis has showed that coordination of uranyl takes place via oxygen atoms in the phosphonic groups, whereas the nitrogen atom remains rather uncoordinated (Kabachnik *et al.*, 1975; Kurzak *et al.*, 2000).

CONCLUSIONS

The obtained results from this study can be summarised as following:

- The HIDMP and DIDMP are synthesised efficiently and rapidly in good yields (85-88%) under microwave irradiation
- The yields of extraction of uranium (VI) increases with the ratio Q. HIDMP and DIDMP can complex and extract respectively 98% and 94% of uranium(VI) by using a large excess extractant agent (Q = 20)
- HIDMP ligand has a stronger extracting power for uranium(VI) than DIDMP. This fact is related to more hydrophobic character of HIDMP vs. DIDMP
- The HIDMP and DIDMP exhibited high complexation efficiency towards uranyl ions. This results from both dinegatively charged phosphonate groups as well as the imino-nitrogen and the hydrophobic character present in their structure
- Logarithmic plots of the uranium (VI) distribution ratio vs. pH_{eq} and the extractant concentration showed that the ratios of extractant to extracted uranium (VI) is 2:1. The metal complexes formed in organic phase are [UO₂(H₃L¹)₂. 2H₂O] and [UO₂(H₃L²)₂. 2H₂O] for HIDMP and DIDMP respectively. Protons, intervening in our extraction, correspond to the pK_a of HIDMP and DIDMP, 3.2 and 3.7 respectively. HIDMP and DIDMP extract the uranyl ions in cationic exchange mode. The two last values of pK_a obtained by potentiometric measurement confirm that the extracting agent can exchange only one or two protons per molecule
- Extraction of uranium(VI) by HIDMP and DIDMP is accompanied by two water molecules extraction
- A spectroscopic analysis has showed that coordination of uranyl takes place via oxygen atoms in the phosphonic groups, whereas the nitrogen atom remains rather uncoordinated
- The equilibrium constants for the extraction of uranium (VI) were found to be 10.45×10⁻³ and 2×10⁻³ for HIDMP and DIDMP, respectively

ACKNOWLEDGMENTS

The authors would like to thank Nuclear Research Center of Draria, King Saud University King Saud University and University of Mouloud Mammeri for his help and encouragement in this research project.

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