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Complex formation of anserine with uranyl in aqueous solution: Thermodynamic studies and structural analysis

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ABSTRACT

Knowledge of uranyl (UO_2^{2+}) aqueous speciation and chemical interactions with natural organic matter is the basis to mode the sorption and transport behavior of uranyl. Anserine is a natural dipeptide containing *β*-alanine and 1-methylhistidine, which can be found in the skeletal muscle of birds and certain species of mammals. The complexation of anserine with uranyl cation was studied thermodynamically and structurally at 25 °C, I = 0.5 mol·L^{-1} NaCl solution. Protonation of anserine was investigated by potentiometry, microcalorimetry and NMR spectroscopy. Experimental results confirmed that there are three successive proton reaction steps for a totally deproton anserine. The order of successive protonation sites are the terminal amine nitrogen atom of alanine, amine nitrogen atoms in imidazole ring, and finally carboxylate oxygen. This trend is in agreement with exothermic enthalpies of protonation reaction. Potentiometry was used to measure stability constant of uranyl complex in solution. Thermodynamic studies identified four uranyl/anserine complexes with different degrees of deprotonation, $UO_2(HL)^{2+}$, UO_2L^{+}, $UO_2L_{2(aq)}$ and $UO_2(OH)L_2^{-}$. Coordination modes of the three complexes [$UO_2(HL)^{2+}$, UO_2L^{+} and $UO_2L_{2(aq)}$] were investigated by NMR spectroscopy. In these complexes, anserine holds a tridentate mode. Cyclic voltammetry was performed to understand the influence of anserine exert over redox response to uranium in solution. The results confirmed that oxidation state of uranyl cation is stabilized significantly and harder to be reduced by complex with anserine. Anserine could effectively suppress the hydrolysis of uranyl in aqueous solutions.

1. Introduction

Uranium is a radioactive heavy metal, which is naturally present in varying concentration in the environment. However, the wide use of uranium for industrial and military applications increases the risk of its distribution in the environment, which is aggravated by such factors as mining activities, uranium processing, or leaching of radioactive wastes [1–3]. Exposure to uranium can result in both chemical and radiological toxicity. This toxicity can be caused by breathing air containing uranium dusts or by eating substances containing uranium, which then enters the blood stream [4]. Uranium forms a large number of chemical species of varying solubility and biological availability. On the basis of the toxicity of different uranium compounds in animals, it was concluded that uranyl cation (UO_2^{2+}), which is known to be the most stable form of uranium under aerial wet conditions and tends to form relatively soluble compounds [5], is more likely to be a systemic toxicant than other valent uranium.

For a better understanding of characterize the interactions of uranyl with organic molecule, knowledge is necessary about structural factors governing uranyl binding and thermodynamic stabilization in biosystems [6–10]. Research in this direction will benefit our understanding of the molecular factors governing uranyl toxicity and speciation in cells and will also aid in developing new molecules for selectively binding uranium that could be used for uranium biodetection or bioremediation purposes.

Histidine-dipeptides play an important role in human and animal tissues. Anserine (*β*-alanyl-*N*-methylhistidine) is a dipeptide containing *β*-alanine and 1-methylhistidine, which can be found in the skeletal muscle and brain of mammals and birds [11, 12]. The functional groups such as carboxyl and amino groups available in anserine can interact with metals through a multi-dentate coordination structure and form various coordination models. However, studies on the complex

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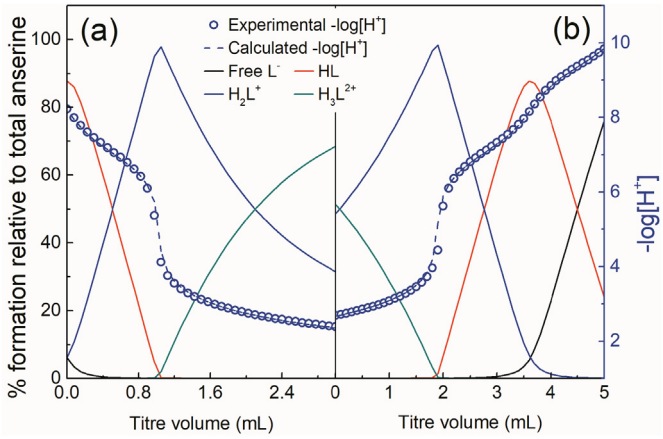

Fig. 1. Multiple potentiometric titrations of anserine at 25 °C. $I = 0.5\ mol{\cdot}L^{-1}$ NaCl. Cup solution: (a), $V^0 = 22.19$ mL, $n_{L^-} = 8.87$ μmol, $n_{H^+} = 8.87$ μmol, titrant: 86.75 $mmol{\cdot}L^{-1}$ HCl; (b), $V^0 = 27.99$ mL, $n_{L^-} = 10.38$ μmol, $n_{H^+} = 32.07$ μmol, titrant: 59.94 $mmol{\cdot}L^{-1}$ NaOH. Symbols (o) – experimental data; dashed blue line – fit (related to right axis, $-\log[H^+]$). Solid lines: aqueous anserine speciation (related to left axis, species %). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

formation of anserine are surprisingly scarce. Only several publications could be found from the literature [13–17].

Our group is especially interested in the thermodynamic studies because they are importance in providing fundamental information on the nature (e.g., ionic bonding vs covalence bonding, outer sphere vs inner sphere), energetics (e. g., free energy, enthalpy, entropy and heat capacity), structures and stabilities of complexes [18–21]. The unique structure of the uranyl cation, a linear dioxo-cation with an overall +2 charge, prevents the use of effective chelating ligands that target spherical cations in three dimensions (e.g. EDTA). Uranyl only allows coordinating atoms to approach the U(VI) atom through its equatorial plane in the complexes. Designed complexants or ligands for the uranyl cation must account for the equatorial coordination sphere available in the uranyl cation and must be able to be arranged on this equatorial plane for effective coordination. This hindrance could somehow place the limitation on the access of some anserine donor atoms to the U(VI) atom in the uranyl/anserine complexes, and thus render the anserine ligand into a specific configuration to accommodate a coordination geometry. From the coordination chemistry point of view, an understanding of those coordination structures could enhance our knowledge of the uranyl coordination behavior with multi-dentate ligands. This paper presents a thermodynamic investigation on the protonation reaction of anserine and complex formation of anserine with uranyl cation, verifying the complexation patterns and explaining the complex strength.

2. Experimental

2.1. Chemicals

All chemicals were reagent grade or higher. Milli-Q water (18.2 MΩ·cm @ 25 °C) was used for preparing solutions. NaCl (≥98%, Aladdin) was chosen as the background electrolyte. A stock solution of anserine (Ark Pharm, 97%) was prepared by dissolving the desired amount of solid sample in the solution containing 0.5 $mol{\cdot}L^{-1}$ NaCl. The uranyl stock solution was prepared by dissolving solid U_3O_8 in hydrochloric acid under low heating. The solution was filtered to remove any undissolved solid. The concentration of U(VI) in stock solution was determined gravimetrically by converting uranyl to U_3O_8 in a crucible at 850 °C. Concentration of free H^+ in the stock solution was determined by Gran titration [22, 23]. The Milli-Q water was boiled in quartz glassware to remove dissolved CO_2 to prepare NaOH solution. Working solutions of NaOH and HCl containing NaCl were standardized by titration with potassium hydrogen phthalate (primary standard, Alfa Aesar) and Trizma base (crystalline, Sigma), respectively. The ionic strength of all working solution was maintained at 0.5 $mol{\cdot}L^{-1}$ (NaCl).

For the NMR experiments, the solution of anserine and uranyl in D_2O was particularly prepared by dissolving a weighed amount of solid sample in D_2O (99.8% D, J&K) and neutralizing it to the desired extent with DCl (Merck, DCl: 35 wt%, D > 99 atom %) and NaOD (Aladdin, NaOD: 40 wt%, D > 99 atom%).

2.2. Potentiometry

Potentiometric experiments were carried out using a specially designed vessel as previously described [24]. The potentiometric vessel consists of a 100 mL glass cell with a lid. Both the cell and the lid are water-jacketed so that the cell temperature can be maintained at 25 °C by water circulating from a constant temperature bath. Experiments are protected by argon throughout the titration to avoid the contamination of carbon dioxide. Electromotive force (EMF, in millivolts) was measured by a potentiometric titrator (888 Titrando, Metrohm) equipped with a pH electrode (Orion™ 8102BN ROSS™ Combination pH Electrode). All the EMF data were corrected for a small contribution from the contact junction potential of hydrogen or hydroxide ion. Corrections for the contact junction potential of the glass electrode in the acidic and basic regions can be expressed by Eqs. (1) and (2).

$$E = E^0 + \frac{RT}{F}\ln[H^+] + \gamma_H[H^+] \quad (1)$$

Table 1
Thermodynamic parameters for complexation of anserine with uranyl.

Reaction	logβ	ΔH, $kJ{\cdot}mol^{-1}$	Solution
$H^+ + L^- = HL$	9.36 ± 0.01	−41.9 ± 0.5	0.5 $mol{\cdot}L^{-1}$ NaCl, 25 °C, this work
	9.51 ± 0.11		0.1 M Na_2SO_4 [15]
	9.45		0.16 M KNO_3 [14]
$H^+ + HL = H_2L^+$	7.10 ± 0.01	−32.0 ± 0.8	0.5 $mol{\cdot}L^{-1}$ NaCl, this work
	6.97 ± 0.14		0.1 M Na_2SO_4 [15]
	7.15		0.16 M KNO_3 [14]
$H^+ + H_2L^+ = H_3L^{2+}$	2.69 ± 0.01	−0.1 ± 1.1	0.5 $mol{\cdot}L^{-1}$ NaCl, this work
	2.60 ± 0.11		0.1 M Na_2SO_4 [15]
$UO_2^{2+} + L^- = (UO_2)L^+$	9.77 ± 0.08		0.5 $mol{\cdot}L^{-1}$ NaCl, 25 °C, this work
$(UO_2)L^+ + H^+ = (UO_2)HL^{2+}$	5.39 ± 0.11		0.5 $mol{\cdot}L^{-1}$ NaCl, 25 °C, this work
$(UO_2)L^+ + L^- = (UO_2)L_2$	4.83 ± 0.12		0.5 $mol{\cdot}L^{-1}$ NaCl, 25 °C, this work
$(UO_2)L_2 + H_2O = (UO_2)(OH)L_2^- + H^+$	−8.91 ± 0.15		0.5 $mol{\cdot}L^{-1}$ NaCl, 25 °C, this work
$H^+ + OH^- = H_2O$	13.7	−56.5	0.5 $mol{\cdot}L^{-1}$ NaCl, 25 °C [30]