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Trace Analysis of Lithium with a Water-Soluble Porphyrin

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Abstract. A water-soluble porphyrin (2,3,7,8,12,13,17,18-octabromo-5,10,15,20-tetrakis(4-sulfonatophenyl)porphyrin; H_2obtpps^{4-}; H_2P^{4-}) was synthesized and developed for the determination and separation of lithium ion in aqueous solution. The octabromo groups lower the basicity of the porphyrin by their electron-withdrawing effect, and enable the porphyrin to react with lithium ion in alkaline aqueous solution to form the lithium complex along with a shift of absorption maxima; λ_{max} (log ϵ/mol^{-1} dm^3 cm^{-1}) of the lithium porphyrin are 490.5 nm (5.31) and 734 nm (4.36). Sodium and potassium ions did not react with the porphyrin. The equilibrium constant for the reaction $Li^+ + HP^{5-} \rightleftharpoons [LiP]^{5-} + H^+$ was found to be $10^{-8.79}$ and the conditional formation constant of the $[LiP]^{5-}$ at pH 13 is $10^{4.21}$. The $[LiP]^{5-}$ can be extracted into chloroform as an ion-pair complex with tetrabutylammonium ion (X^+) and the extracted X_5LiP dissociates to X_4LiP^- and X^+ in chloroform. The extraction constant for the reaction of $[LiP^{5-}]_a + 5[X^+]_a \rightleftharpoons [X_4LiP^-]_o + [X^-]_o$ was found to be $(8.4 \pm 0.7) \times 10^{12}$ mol^{-4} dm^{12}, where subscripts of a and o denote chemical species in aqueous and organic phases, respectively. The above results were developed for the determination of lithium in serum, sea water and hot spring water samples at a range of 0.07–0.7 mg dm^{-3} ($1 \times 10^{-5} - 1 \times 10^{-4}$ mol dm^{-3}). The interference of heavy metal ions was masked by N,N′-1,2-ethanediylbis[N-(carboxylmethyl)glycinato]magnesium(II) ([Mg(edta)]$^{2-}$ or H_4edta if sample contain magnesium(II) ion.

Key words: lithium porphyrin, spectrophotometry, solvent extraction, serum, sea water

1. Introduction

Porphyrins and metalloporphyrins have for a long time been a subject of considerable interest in a variety fields, because of their biological importance in plants and animals, and the chemistry of porphyrin compounds has been reviewed by Falk [1], Dolphin [2] and Smith [3]. The porphyrins are also attractive compounds from an analytical point of view due to their very high molar absorptivity reaching several hundred thousand mol^{-1} dm^3 cm^{-1} at 400–500 nm (the so-called Soret band) and unique characters, which are not observed for open chain ligands, like slow metalation rates and the catalytic effect of large metal ions on the metalation [4]. Banks and Bisque [5] were the first to propose porphyrin as a reagent for zinc(II) in 1957, but little work was done until Ishii and Yotsuyanagi's groups published a series of

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papers dealing with the use of porphyrins for the determination of Cu, Pb, Cd and Zn some twenty years later [6]. However, porphyrins have not been utilized for the determination or the separation of Li due to the difficulty in the formation of the Li-porphyrin complex. Some lithium porphyrins were used as intermediates in the synthesis of more stable metalloporphyrins [7] and were isolated under nonaqueous conditions by Arnold [8–10] and Tsuchiya [11]. However, the coordinated Li^+ of these porphyrins dissociates from the porphyrins upon the addition of water.

Lithium has been used for the treatment of mania and depression [12] and for lithium batteries [13, 14]. Such applications require methods for selective and sensitive determination and separation of lithium ion in a large excess of sodium ion. The most recent analyses for Li^+ use ion-selective electrodes [15] and colorimetric methods based on crown ethers which have chromophores [16–18]. A water-soluble porphyrin becomes a prospective analytical reagent if the lithium complex is stable in aqueous solution.

The selectivity of alkali metal ion depends on the cavity size of reagents like crown ethers [19]. Porphyrins show high selectivity for metal ions due to a definite cavity size (400 pm in diameter) that accommodates medium-sized metal ions like nickel(II), copper(II) and zinc(II) [20, 21]. We noticed that the ionic size of a lithium ion (73 pm) is comparable to zinc(II) (74 pm) [22] which was selectively determined in a large excess of cadmium(II) and lead(II) [23, 24]. A weak point of porphyrins is that the lithium porphyrin is unstable in aqueous solution due to hard dissociation of the proton from the pyrrole nitrogen. Deprotonation occurs at pH $>$ 14 for conventional water-soluble porphyrins [25]. In order to solve this problem, we synthesized a new water-soluble porphyrin with eight bromine atoms which makes it easy to release protons bound to the pyrrole nitrogen atoms of the porphyrin by their electron-withdrawing effect [26]. The synthesized porphyrin can exist in the form of an iminate (N^- of pyrrole) in alkaline solution. The iminate ion can strongly bind with lithium. We describe here a selective and sensitive colorimetric and separation method of lithium ion in aqueous solution using a water-soluble porphyrin.

2. Experimental

2.1. Synthesis of porphyrin

2, 3, 7, 8, 12, 13, 17, 18-Octabromo-5, 10, 15, 20-tetrakis(4-sulfonatophenyl) porphyrin (H_2obtpps^{4-}, Figure 1) was synthesized by the bromination and sulfonation of 5,10,15,20-tetraphenylporphyrin (H_2tpp) as follows: H_2tpp (1 g, 1.63 m mol) was treated with *N*-bromosuccinimide (NBS, 3 g, 16.8 m mol) instead of bromine previously reported [27] in dibromomethane which was sufficiently dried by molecular sieve (4 Å) before use. The crude product gave three bands on an activated alumina chromatography (300 mesh, Wako, Japan) using chloroform as eluent and the first band was collected. Yield was 53%. Absorption maximum-wave lengths of the product, 2,3,7,8,12,13,17,18-

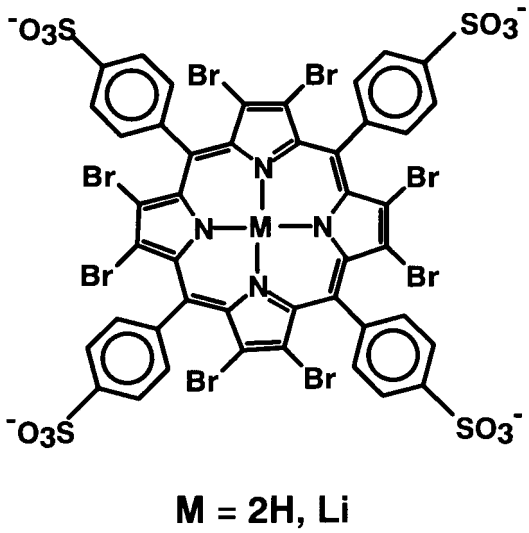


Figure 1. 2,3,7,8,12,13,17,18-Octabromo-5,10,15,20-tetrakis(4-sulfonatophenyl)porphyrin (H_2obtpps^{4-}) and its lithium complex (Li(obtpps)$^{5-}$).

octabromo-5,10,15,20-tetraphenylporphyrin (H_2obtpp, **1**), were 370, 469, 569, 626 and 743 nm in chloroform. Chemical shifts of ^{1}H NMR of the product were 7.79 ppm (*m*, 12 H, for *m*- and *p*-H of phenyl) and 8.19 ppm (d, 8H, *o*-H of phenyl) in $CDCl_3$ vs. TMS, respectively. The compound **1** was sulfonated in concentrated sulfuric acid. The product was precipitated by careful addition of a small amount of water and purified by a Sephadex column LH-20 which was soaked in a water-methanol (7 : 3) mixed solvent. Absorption maxima (log ϵ/mol^{-1} dm^3 cm^{-1}) of the final product, H_2obtpps^{4-}, were 376 (4.54), 478 (5.30), 657 (4.25) and 760 nm (4.07) in aqueous solution at pH 7.0 and ^{1}H NMR data (δ/ppm) 8.62 (d, 8H, *o*-H of phenyl) and 8.09 (d, 8H, *m*-H of phenyl) in d_6-dimethylsulfoxide.

2.2. General procedure

Absorption spectra were recorded on a Shimadzu UV-2100 and a Jasco Ubest spectrophotometer at various pHs and concentrations of lithium and the porphyrin. The pH values were measured with a radiometer Ion 85 analyzer with a combined electrode (GK2401C) using a 1.000×10^{-2} mol dm^{-3} nitric acid solution containing 0.09 mol dm^{-3} sodium nitrate as the standard hydrogen ion concentration ($-\log[H^+] = 2.000$). The pH meter and electrode system was calibrated in terms of $-\log[H^+]$ at an ionic strength of 0.1 mol dm^{-3} (HNO_3—$NaNO_3$).

Solvent extraction was carried out as follows. 10 mL chloroform was added to a 10-mL aqueous solution containing lithium ion (10^{-5}–10^{-2} mol dm^{-3}), H_2obtpps^{4-} (5×10^{-6} mol dm^{-3}), tetrabutylammonium chloride (10^{-5}–10^{-3} mol dm^{-3}), buffer (2-(4-(2-hydroxyethyl)-1-piperadinyl)ethanesulfonic acid, HEPES)

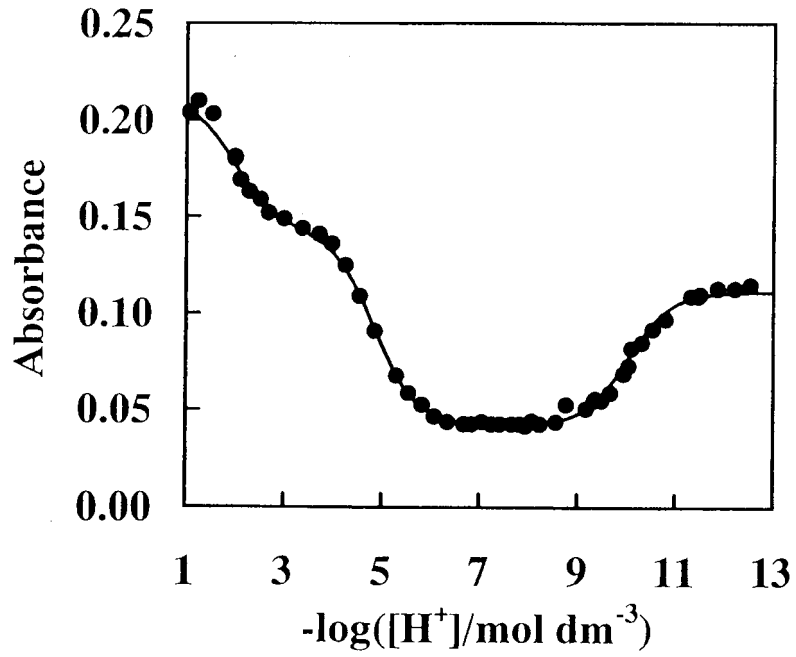


Figure 2. Change in absorbance of H_2obtpps^{4-} at 720 nm in various $-\log[H^+]$ and at [H_2obtpps^{4-}] = 6.68×10^{-6} mol dm^{-3} and I = 0.1 ($NaNO_3$). The solid line was calculated by using K_1, K_2 and K_{-1} values listed in Table I.

or NaOH and NaCl (0.1 mol dm^{-3}). The mixture of aqueous solution with chloroform was shaken for 5 min mechanically and centrifuged for 10 min at 2000 rpm. All experiments were carried out at 25 °C.

3. Results and Discussion

3.1. Protonation constant of H_2obtpps^{4-} in aqueous solution

Absorption spectra of H_2obtpps^{4-} in aqueous solution were measured in various pH values at an ionic strength of 0.1 mol dm^{-3} ($NaNO_3$). The absorption maxima were observed at 490 and 740 nm at pH lower than 2, 475 and 660 at pH 6–8.2 and 505 and 745 nm at pH higher than 11. The absorbance at 720 nm is plotted against $-\log[H^+]$ in Figure 2. The change in absorbance suggests three steps of proton-equilibria and their equilibirum constants as given in Equations (1)–(3):

$$H^+ + H_2P^{4-} \rightleftharpoons H_3P^{3-};\ K_1 \quad (1)$$

$$H^+ + H_3P^{3-} \rightleftharpoons H_4P^{2-};\ K_2 \quad (2)$$

$$H_2P^{4-} \rightleftharpoons HP^{5-} + H^+;\ K_{-1} \quad (3)$$

Table I. Protonation and deprotonation constants of H_2obtpps^{4-} and formation constant of Li(obtpps)$^{5-}$ [a]

Equilibrium[b]	Constants
$\log(K_1/\text{mol}^{-1}\ \text{dm}^3)$	4.83 ± 0.04
$\log(K_2/\text{mol}^{-1}\ \text{dm}^3)$	1.96 ± 0.06
$\log(K_{-1}/\text{mol dm}^{-3})$	-10.02 ± 0.02
$\log(K_{\text{LiP}})$	-8.79 ± 0.02

[a] At 25 °C and I = 0.1 ($NaNO_3$).
[b] The equilibrium constants are defined as
$K_1 = [H_3P^{3-}][H^+]^{-1}[H_2P^{4-}]^{-1}$,
$K_2 = [H_4P^{2-}][H^+]^{-1}[H_3P^{3-}]^{-1}$,
$K_{-1} = [HP^{5-}][H^+][H_2P^{4-}]^{-1}$,
$K_{\text{LiP}} = [LiP^{5-}][H^+][Li]^{-1}[HP^{5-}]^{-1}$.
H_2P^{4-} denotes a free-base form of porphyrin (H_2obtpps^{4-}).

where H_2P^{4-} denotes the free-base form of the porphyrin which is the main chemical species in neutral pH. The equilibrium constants are summarized in Table I. The K_1 value is about 1000 times larger than that of K_2, although the K_1 and K_2 values of non-deformed porphyrin like 5,10,15,20-tetrakis(4-sulfonatophenyl)porphyrin (H_2tpps^{4-}) are very similar to each other; $\log(K_1/\text{mol}^{-1}\ \text{dm}^3)$ and $\log(K_2/\text{mol}^{-1}\ \text{dm}^3)$ are 4.99 and 4.76, respectively [25]. Computer calculation (MM+ on the software HyperChem™ program) of H_2obtpps^{4-} indicated the deviation of the pyrrole ring by 23.6° from the mean porphyrin plane. Generally, the deformation of the porphyrin separates the two protonation constants; the basicity for the first protonation increases, but that for the second protonation decreases due to a decrement in π-conjugation of the porphyrin core [28]. Another effect of bromination is to lower the basicity of the porphyrin by the electron-withdrawing effect. Interestingly, the deprotonation of the free-base form, H_2obtpps^{4-}, was observed at ∼pH 10. Most of the non-deformed free-base porphyrins hardly dissociates protons even in a strong alkaline medium, e.g., the deprotonation of H_2tpps^{4-} occurs at pH more than 14.

3.2. Formation of lithium porphyrin in aqueous solution

H_2obtpps^{4-} reacted with lithium hydroxide to shift the absorption spectrum towards shorter wavelength. But sodium hydroxide and potassium hydroxide did not alter the absorption spectra (Figure 3). The absorption maximum wavelengths (log $\epsilon/\text{mol}^{-1}\ \text{dm}^3\ \text{cm}^{-1}$) of the lithium(I) porphyrin complex are 490.5 nm (5.31) and 734 nm (4.36). Non-brominated porphyrin, i.e., H_2tpps^{4-}, did not give any spectral change even in 0.1 mol dm^{-3} LiOH. This behavior is unique to H_2obtpps^{4-}. The octabromo groups decrease the basicity of the porphyrin so that the proton in the pyrrole group is released even at pH 10. That makes it easy for lithium ions to react with the porphyrin.

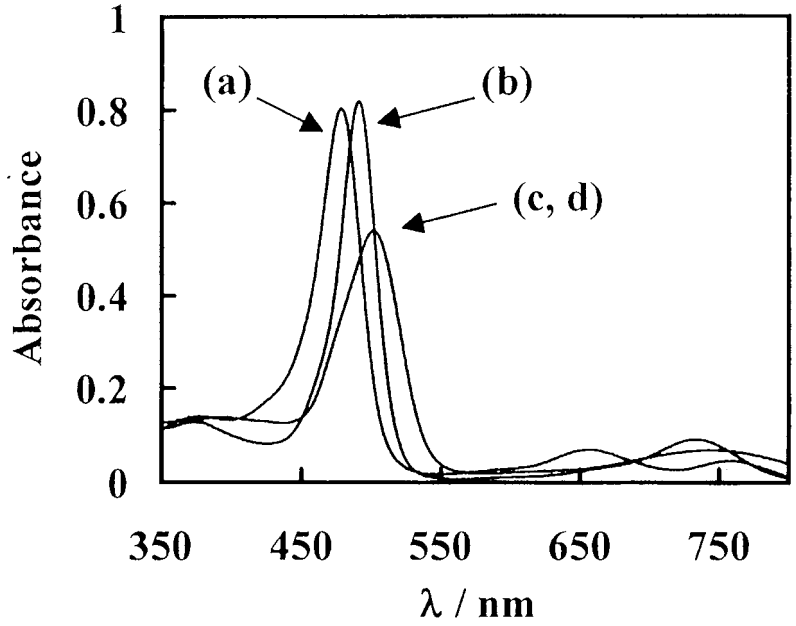


Figure 3. Change in absorption spectra of H_2obtpps^{4-} (4.0×10^{-6} mol dm^{-3}) in pH 7.0 (a), 0.1 mol dm^{-3} LiOH (b), 0.1 mol dm^{-3} NaOH (c) and 0.1 mol dm^{-3} KOH (d).

The equilibrium constant of the lithium(I) porphyrin complex was determined from the change in absorption spectra of the porphyrin at different concentrations of lithium ion (10^{-6}–10^{-2} mol dm^{-3}) (Figure 4) and sodium hydroxide (pH 11.7–12.3). The data suggest that one lithium ion reacts with HP^{5-} to form [LiP]$^{5-}$ by releasing one hydrogen ion at pH higher than 11:

$$Li^+ + HP^{5-} \rightleftharpoons [LiP]^{5-} + H^+ \quad (4)$$

The equilibrium constant of Equation (4) is given in Table I with the protonation constant of the free-base porphyrin at 25 °C and I = 0.1 mol dm^{-3} ($NaNO_3$).

Arnold et al. reported that one and two lithium atoms bind to porphyrins in organic solvents [9, 10], but only the 1 : 1 complex, [LiP]$^{5-}$, was formed for H_2obtpps^{4-} in aqueous solution.

Since the ionic radius of lithium(I) (73 pm) is comparable to that of zinc(II) (74 pm) [22], lithium can incorporate well into the core of H_2obtpps^{4-} like zinc(II) porphyrin [29]. Sodium and potassium ions, however, cannot form stable complexes with H_2obtpps^{4-} because of the large ionic radii of sodium (113 pm) and potassium (151 pm) [22].

It is interesting to note how [LiP]$^{5-}$ is stable compared to lithium(I) crown-ether complexes. Although the equilibrium constant for the reaction $Li^+ + P^{6-} \rightleftharpoons [LiP]^{5-}$ could not be determined, the conditional formation constant defined by $K' = [LiP^{5-}][Li^+]^{-1}[(P^{6-})']^{-1}$ was calculated to be $10^{4.21}$ in 0.1 mol dm^{-3}

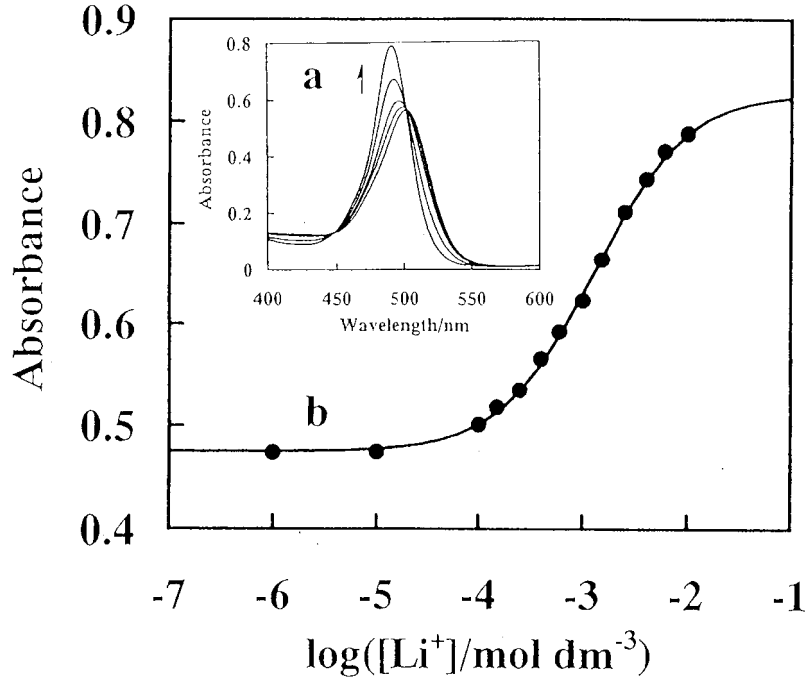


Figure 4. Typical spectral change of H_2obtpps^{4-} (3.76×10^{-6} mol dm^{-3}) in the presence of lithium(I) at pH 11.7 (a) and the absorbance at 490.5 nm plotted against the concentration of lithium (I) (b).

NaOH from the formation constant (K_{LiP}) of [LiP]$^{5-}$ and deprotonation constant of H_2obtpps^{4-} (log K_{-1}) values, where [(P^{6-})′] denotes the total concentration of the porphyrin unbound to lithium(I). The equilibrium constant is much larger than the formation constants of lithium complexes with crown-ethers in aqueous solution [19].

3.3. SOLVENT EXTRACTION

3.3.1. *Distribution of Free-Base and Lithium Porphyrins between Water and Chloroform*

The free-base and lithium porphyrins are extracted into chloroform in the presence of tetrabutylammonium chloride (But$_4$NCl: XCl) from aqueous phase. The distribution ratio ($D = C_{\mathrm{p,o}}/C_{\mathrm{p,a}}$) are shown in Figure 5 for H_2P^{4-} and [LiP]$^{5-}$ at the various concentrations of But$_4$NCl, where $C_{\mathrm{p,o}}$ and $C_{\mathrm{p,a}}$ are the total concentrations of porphyrins in organic and aqueous solutions, respectively. The concentration of But$_4$N$^+$ in the aqueous phase was calculated by using the extraction constants of But$_4$NCl ($\log K_{\mathrm{ex(But_4NCl)}} = \log([\mathrm{But_4NCl}]_{\mathrm{o}}/[\mathrm{But_4N^+}]_{\mathrm{a}}[\mathrm{Cl^-}]_{\mathrm{a}})$ = 0.07 [30]) at $[\mathrm{Cl^-}]_{\mathrm{a}}$ = 0.1 mol dm^{-3}) and of But$_4$NOH ($\log K_{\mathrm{ex(But_4NOH)}}$ =

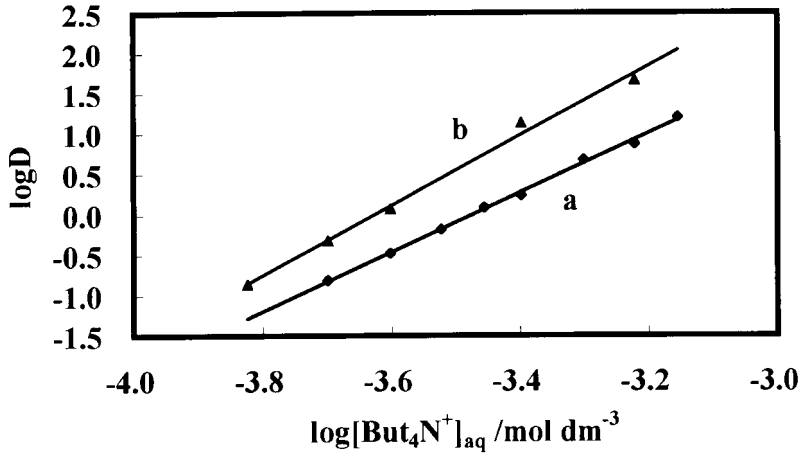
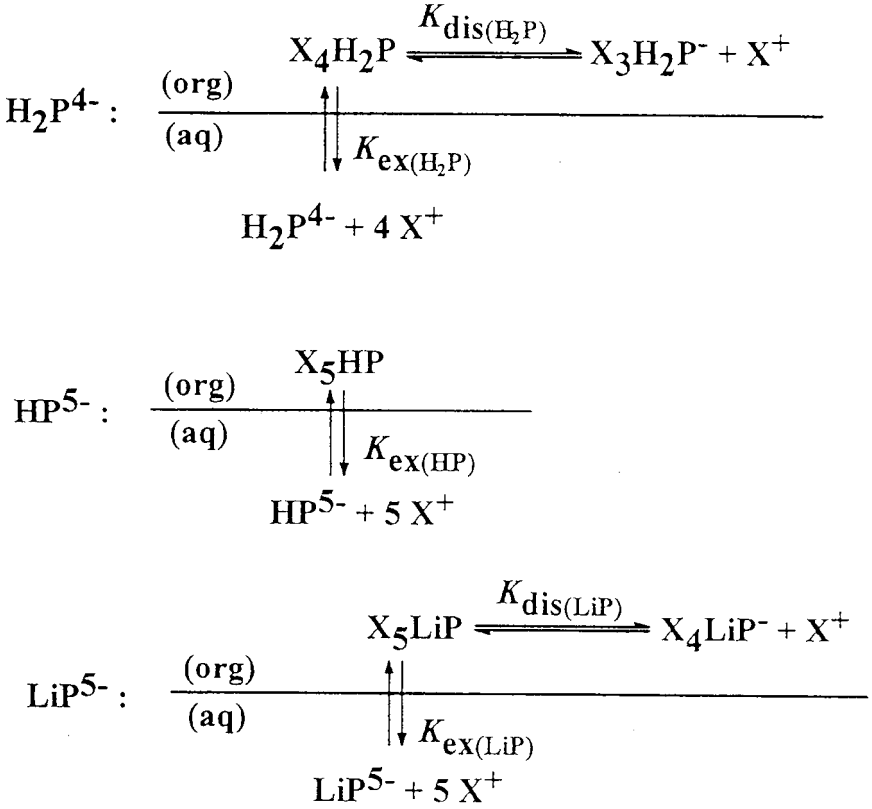


Figure 5. Distribution of free-base porphyrin (a) at pH 7.5 and lithium porphyrin (b) at pH 12.7 and $[Li^+] = 1 \times 10^{-2}$ mol dm^{-3} at various log[But_4N^+] and [H_2obtpps^{4-}] = 4.87 × 10^{-6} mol dm^{-3}.

log([$But_4NOH]_o$/[$But_4N^+]_a[OH^-]_a$) = −0.83 [31]) at $[OH^-]_a$ = 0.1 mol dm^{-3}. The slopes of the straight lines are 3.30 ± 0.16 and 4.20 ± 0.08 for H_2P^{4-} and $[LiP]^{5-}$, respectively. The data indicate dissociation of $(But_4N)_4H_2P$ and $(But_4N)_5LiP$ to $[(But_4N)_3H_2P]^-$ and $[(But_4N)_4LiP]^-$ in chloroform, respectively. For the extraction of HP^{5-}, the ion-pair complex of H_2P^{4-} was extracted even at pH 12.7, where the main chemical species in the aqueous phase is HP^{5-} (see Table I). The deprotonated porphyrin (HP^{5-}) was hardly extracted with tetrabutylammonium ion into chloroform. This may come from the high solvation of water to the iminate ion of pyrrole nitrogen.

3.3.2. *Extraction Equilibrium of Free-Base and Lithium Porphyrins*

The free-base and lithium porphyrins are extracted into chloroform as an ion-pair complex with tetrabutylammonium and the extracted species dissociate in chloroform. Thus, the extraction mechanism of the porphyrins is given in Scheme 1. Absorbances of extracted H_2P^{4-}, HP^{5-} and $[LiP]^{5-}$ in chloroform are plotted against $[But_4N^+]_a$ in Figures 6 and 7. Since the extraction mechanism is complicated, the extraction constants of H_2P^{4-} and HP^{5-} were analyzed separately at pH 7.5 and 12.7, respectively, where only H_2P^{4-} and HP^{5-} exist, respectively, in aqueous phase. The determined equilibrium constants were also checked again by an experiment at pH 10, where both H_2P^{4-} and HP^{5-} exist in aqueous phase and $[HP^{5-}]/[H_2P^{4-}] = 1$. Similarly, the extraction constant of $[LiP]^{5-}$ was determined at pH 12.7 and at $[Li^+]$ = 0.01 mol dm^{-3}, where $[LiP]^{5-}$ is main chemical species in aqueous solution.



Scheme 1. Extraction equilibrium of H_2P^{4-}, HP^{5-} and $[LiP]^{5-}$ into chloroform in the presence of tetrabutylammonium chloride.

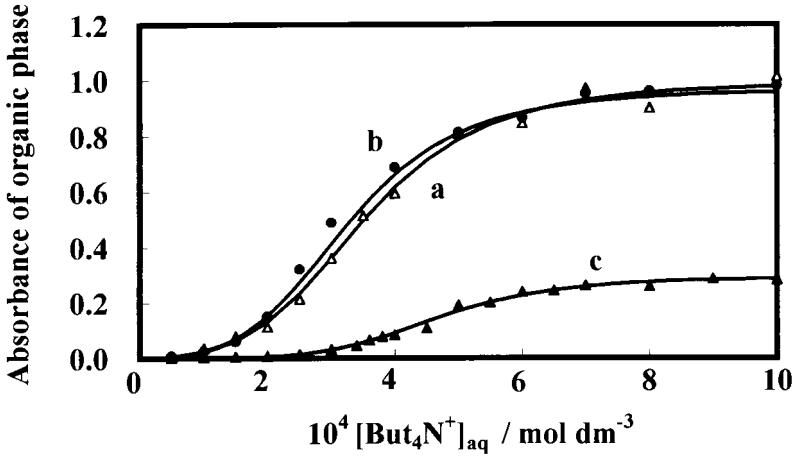


Figure 6. Extraction of porphyrin at pH 7.5 (a), pH 10 (b) and pH 12.7 (c) and $[H_2obtpps^{4-}] = 4.34 \times 10^{-6}$ mol dm^{-3} in various $[But_4N^+]_a$. Solid lines were calculated by using the values of $K_{ex(H_2P)}$, $K_{dis(H_2P)}$ and $K_{ex(HP)}$ listed in Table II.

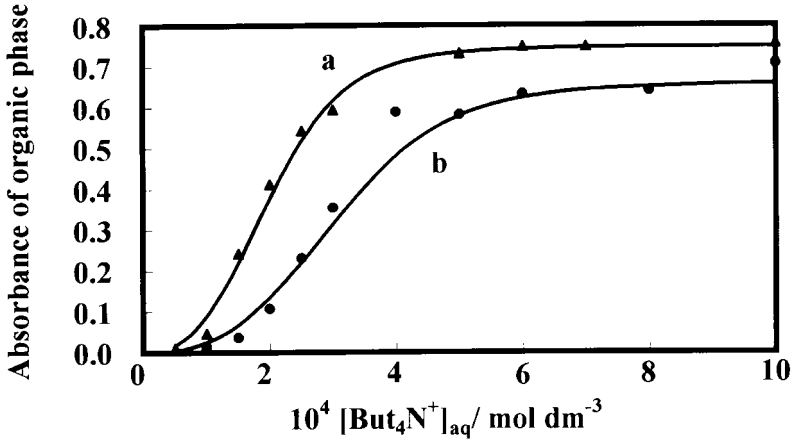


Figure 7. Extraction of lithium porphyrin at $[Li^+]$/mol $dm^{-3} = 1 \times 10^{-2}$ (a) and 1×10^{-5} (b) and $[H_2obtpps^{4-}] = 4.87 \times 10^{-6}$ mol dm^{-3}in various $[But_4N^+]_a$. Solid lines were calculated by using the values of $K_{ex(LiP)}$ $K_{dis(LiP)}$ listed in Table II.

The average molar absorptivity (ϵ = Abs,o/C_p) of H_2P^{4-} at pH 7.5 in organic phase is expressed as a function of extraction and dissociation constants and the concentration of tetrabutylammonium ion follows:

$$\bar{\epsilon} = \frac{\epsilon_1(K_{ex(H_2P)}[X^+]_a^4 + K_{dis(H_2P)}K_{ex(H_2P)}[X^+]_a^4/[X^+]_o)}{1 + K_{ex(H_2P)}[X^+]_a^4 + K_{dis(H_2P)}K_{ex(H_2P)}[X^+]_a^4/[X^+]_o} \tag{5}$$

Similarly, the average molar absorptivity of HP^{5-} at pH 12.7 is given by the following equation with consideration of the partition of X_4H_2P and $X_3H_2P^-$ into chloroform.

$$\bar{\epsilon} = \frac{\epsilon_1(K_{ex(H_2P)}[X^+]_a^4 + K_{dis(H_2P)}K_{ex(H_2P)}[X^+]_a^4/[X^+]_o) + \epsilon_2 K_{ex(HP)}K_{-1}[X^+]_a^5/[H^+]_a}{K_{-1}/[H^+]_a + K_{ex(H_2P)}[X^+]_a^4 + K_{dis(H_2P)}K_{ex(H_2P)}[X^+]_a^4/[X^+]_o + K_{ex(HP)}K_{-1}[X^+]_a^5/[H^+]_a} \tag{6}$$

where, ϵ_1 and ϵ_2 denote molar absorptivities of the extracted H_2P^- and HP^{5-}, respectively, in chloroform. For the extraction of $[LiP]^{5-}$, the change in absorbance in Figure 7 is correlated to the equilibrium constants involved in Scheme 1 as follows:

$$\bar{\epsilon} = \frac{\epsilon_3 K_{dis(LiP)}K_{ex(LiP)}[X^+]_a^5/[X^+]_o}{1 + K_{dis(LiP)}K_{ex(LiP)}[X^+]_a^5/[X^+]_o} \tag{7}$$

where ϵ_3 denotes the molar absorptivity of $[X_4LiP]^-$ in chloroform and the equilibrium constants are defined for the extraction of H_2P^{4-}, HP^{5-} and LiP^{5-}

Table II. Extraction constants of the porphyrin and the lithium porphyrin with tetrabutylammonium into chloroform[a]

Equilibrium[b]	Constants
$K_{ex(H_2P)}$/mol^{-4} dm^{12}	$(9.5 \pm 1.5) \times 10^{13}$
$K_{dis(H_2P)}$/mol dm^{-3}	$(3.5 \pm 0.7) \times 10^{-7}$
$K_{ex(HP)}$/mol^{-5} dm^{15}	$(4.7 \pm 0.4) \times 10^{16}$
$K_{ex(LiP)}K_{dis(LiP)}$/mol^{-4} dm^{12}	$(8.4 \pm 0.7) \times 10^{12}$

[a] At 25 °C and I = 0.1 ($Na^+(Cl^-, OH)^-$).
[b] The extraction and dissociation constants are defined as below for H_2P^{4-}, HP^{5-} and $[LiP]^{5-}$, respectively:
$K_{ex(H_2P)} = [X_4H_2P]_o/[H_2P^{4-}]_a\,[X^+]_a^4$;
$K_{ex(HP)} = [X_5HP]_o/[HP^{5-}]_a\,[X^+]_a^5$;
$K_{ex(LiP)} = [X_5LiP]_o/[LiP^{5-}]_a\,[X^+]_a^5$;
$K_{dis(H_2P)} = [X_3H_2P^-]_o\,[X^+]_o/[X_4H_2P]_o$;
$K_{dis(LiP)} = [X_4LiP^-]_o[X^+]_o/[X_5LiP]_o$.

as follows. $K_{ex(H_2P)} = [X_4H_2P]_o/[H_2P^{4-}]_a\,[X^+]_a^4$; $K_{ex(HP)} = [X_5HP]_o/[HP^{5-}]_a\,[X^+]_a^5$; $K_{ex(LiP)} = [X_5LiP]_o/[LiP^{5-}]_a\,[X^+]_a^5$; $K_{dis(H_2P)} = [X_3H_2P^-]_o\,[X^+]_o/[X_4H_2P]_o$; $K_{dis(HP)} = [X_4HP^-]_o\,[X^+]_o/[X_5HP]_o$; $K_{dis(LiP)} = [X_4LiP^-]_o[X^+]_o/[X_5LiP]_o$; $K_{-1} = [HP^{5-}][H^+][H_2P^{4-}]^{-1}$. These equilibrium constants were determined from the change in absorbance at different pHs and concentrations of tetrabutylammonium chloride by applying a least-squares minimization program to Equations (5)–(7). The determined values are summarized in Table II. The solid lines in Figures 6 and 7 are calculated from these equilibrium constants and fit well with the experimental data. The distribution curve of the chemical species in the organic phase is depicted at $[Li^+] = 1 \times 10^{-3}$ mol dm^{-3} in Figure 8.

The main chemical species is $[LiP]^{5-}$ at pH > 12 and lithium ions at a therapeutic concentration (0.5–1.5 mmol dm^{-3}) are completely extracted at pH > 12.

3.4. Application of H_2obtpps^{4-} to the determination of lithium in real samples

The synthesized water soluble porphyrin forms a stable lithium complex in aqueous solution. The results were developed for the determination of lithium ion in aqueous solution [32]. The general procedure is as follows. A 5-mL water sample containing 0.7–7.0 μg of lithium(I) was taken into a 10-mL calibrated flask. Then, 1 mL of *N*,*N*′-1,2-ethanediylbis[N(carboxylmethyl)glycinato]magnesium(II) ($[Mg(edta)]^{2-}$) solution ($C_{Mg} = 1.1 \times 10^{-2}$ mol dm^{-3}; $C_{H_4edta} = 1.0 \times 10^{-2}$ mol dm^{-3}), 1 mL of H_2obtpps^{4-} (3.8×10^{-5} mol dm^{-3}), and 0.5 mL of 1 mol dm^{-3} NaOH were added

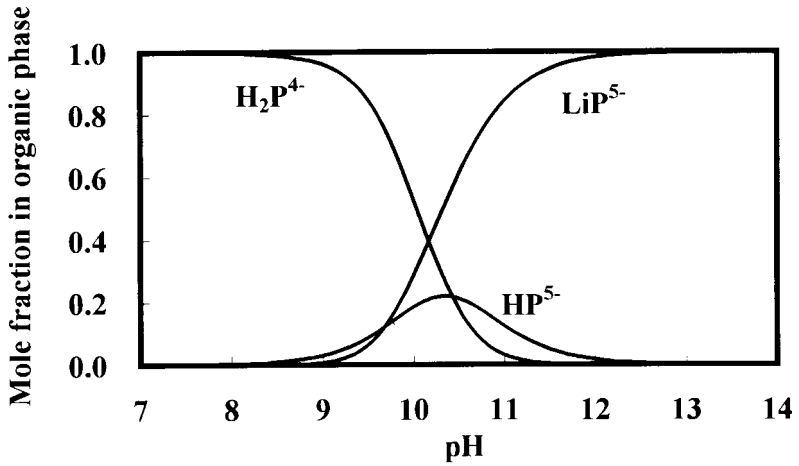


Figure 8. Distribution curve of H_2P^{4-}, HP^{5-} and LiP^{5-} in the organic phase at different pH, $[H_2obtpps^{4-}] = 5 \times 10^{-6}$ mol dm^{-3} and $[Li^+] = 1.0 \times 10^{-3}$ mol dm^{-3}.

to the flask. Distilled water was added to the mark (10 mL) and the absorbance at 490 nm was measured against a blank solution. A calibration graph was linear over the range of 1×10^{-5}–1×10^{-4} mol dm^{-3} of lithium(I) with a correlation factor of 0.967. Lithium ion less than a ppm level was determined spectrophotometrically in aqueous solution.

3.4.1. *Effect of Foreign Ions on the Determination of Lithium*

Since the porphyrin forms stable complexes with transition and heavy metal ions, these metal ions were masked by $[Mg(edta)]^{2-}$ in ligand buffer. We determined the optimum condition for the ligand buffer solution to mask transition and heavy metal ions for the determination of lithium in a sample solution. In order to mask metal M (zinc(II), copper(II) etc.) as completely as possible, most of M should be in the form of $[M(edta)]^{2-}$ and lithium should be the free ion. Magnesium(II) used as a component of the ligand buffer for masking the metal M should satisfy the conditions: $K_{M(edta)} > K_{Mg(edta)} > K_{Li(edta)}$. The formation constants (logarithmic values) of copper(II), zinc(II), magnesium(II) and lithium(I) are 18.70, 16.44, 8.83 and 2.79, respectively [33]. Thus, $[Mg(edta)]^{2-}$completely masks metal ions such as copper(II) and zinc(II). Cations usually encountered in environmental samples were masked by $[Mg(edta)]^{2-}$. Anions (Cl^-, Br^-, F^-, SCN^-, CO_3^{2-}, SO_4^{2-} and PO_4^{3-}) more than 10^{-5} mol dm^{-3} did not interfere with the determination of lithium(I). In particular, chloride as high as 10^{-1} mol dm^{-3} did not give any effect on the determination of 1.0×10^{-4} mol dm^{-3} of lithium(I).

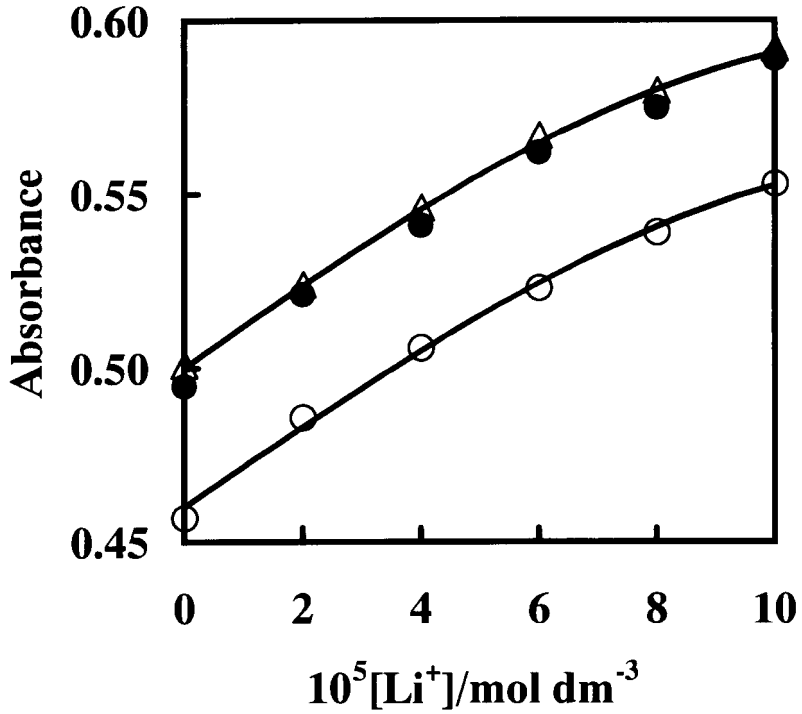


Figure 9. Recovery of lithium by addition of accurate amounts of lithium to serum with (●) and without (○) the protein removing procedure and to pure water (△) at $[H_2obtpps^{4-}]$ = 3.84×10^{-6} mol dm^{-3}, $[H_4edta] = 1.00 \times 10^{-4}$ mol dm^{-3} and [NaOH] = 0.05 mol dm^{-3}.

3.4.2. *Application of the Proposed Method to Serum, Sea Water and Hot Spring Water Samples*

The present method was applied to the determination of lithium ion(I) in human blood serum, sea water and hot spring water.

(a) *Human Blood Sample*

Protein reacted with porphyrin and reduced absorbance. Thus, the protein in serum was removed using the following procedure. Human blood was centrifuged at 3000 rpm and 1 mL of the upper serum was transferred slowly to a trichloroacetic acid solution (5 g/50 cm^3) under stirring. The sample was left for 10 min followed by centrifugation at 3000 rpm for 30 min. Trichloroacetic acid in the supernatant was completely removed by extracting 5 times using diethyl ether. The aqueous phase was reduced to ca. 1 mL of volume, and the sample was analyzed by the method described above. Since serum contains a few mmolar of Mg^{2+}, H_4edta ($[H_4edta] = 1.00 \times 10^{-4}$ mol dm^{-3}) in place of $[Mg(edta)]^{2-}$ was added to mask other metal ions in the serum. Since the sample did not contain lithium ion, we checked the recovery of lithium ion by the addition of accurate amounts of standard lithium concentration. The final concentration of Li^+ was in the order of (1–10)

$\times 10^{-5}$ mol dm^{-3}. The results are shown in Figure 9. The recovery was greatly reduced for the procedure without protein removal. It is clear that protein binds the porphyrin and interferes with the formation of the lithium porphyrin.

(b) *Sea Water and Hot Spring Water*
Large amounts of sodium ion did not interfere with the determination of lithium ion for the present method, but magnesium(II) ion more than 10^{-3} mol dm^{-3} did interfere a little. Thus, an amount of H_4edta equivalent to the total magnesium ion was added to the sea water sample to make $[Mg(edta)]^{2-}$. Lithium ion in the sea water sample was determined by the standard addition method using a calibration graph measured at the same ionic strength as the sea water. The concentration of lithium ion in sea water was found to be $(1.99 \pm 0.04) \times 10^{-5}$ mol dm^{-3}. The concentration obtained was checked by flame photometry and it was $(1.57 \pm 0.09) \times 10^{-5}$ mol dm^{-3}. The small difference in the concentration of lithium detected by the two methods may arise from an interference of sodium ion in the flame method. The concentration of lithium in the hot spring water was so much less than 10^{-6} mol dm^{-3} that its concentration could not be determined by the present method, but a recovery test using the hot spring water was sufficient; zinc and iron in the hot spring water were completely masked by $[Mg(edta)]^{2-}$.

4. Conclusions

Present studies propose the first example for the direct spectrophotometric determination of lithium less than 1 ppm in water and the separation of lithium using a water-soluble porphyrin. NaCl more than 0.1 mol dm^{-3} did not interfere with the determination of lithium ion and the interference of heavy and transition metal ions was masked by $[Mg(edta)]^{2-}$ or H_4edta if the sample contained a large amount of Mg^{2+}. The method was applicable to the determination of lithium in serum and sea water.

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