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Electrochemical study of the complexes of aspartame with Cu(II), Ni(II) and Zn(II) ions in the aqueous medium

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Dedicated to Professor Dr Petr Zuman with regard to his contributions to polarography

Abstract

The voltammetric behaviours of aspartame in the presence of some metal ions (Cu(II), Ni(II), Zn(II)) were investigated. In the presence of aspartame, copper ions reduced at two stages with quasi-reversible one-electron and, with increasing the aspartame (L) concentration, Cu(II)L_2 complex reduces at one-stage with irreversible two-electron reaction (-0.322 V). Zn(II)–aspartame complex ($\log \beta = 3.70$) was recognized by a cathodic peak at -1.320 V. Ni(II)–aspartame complex ($\log \beta = 6.52$) is reduced at the more positive potential (-0.87 V) than that of the hydrated Ni(II) ions (-1.088 V). In the case of the reduction of Ni(II) ions, aspartame serves as a catalyst. From electronic spectra data of the complexes, their stoichiometries of 1:2 (metal–ligand) in aqueous medium are determined. The greatness of these logarithmic values is agreement with Irwing–Williams series (Ni < Cu > Zn).

Keywords: Aspartame; Copper; Nickel; Zinc; Electrochemistry; Catalytic effect; Binary complexes

1. Introduction

Aspartame (*N*-L-α-aspartyl-L-phenylalanine-1-methyl ester, Scheme 1) a low-calorie sweetener obtained by synthesis from two amino acids, L-phenylalanine and L-aspartic acid, is very widely used in foods, soft drinks and dietary products.[1]

Clinical studies showed that the usage of the excess aspartame causes to the various health problems such as headaches, migraines,[2] memory loss. The investigation of the complexes of metal ions (such as Cu, Ni, and Zn) which are vital for biological systems and can be present at the foods, is important because it can serve the clarification of clinical results. As apparent the formula (Scheme 1), aspartame can also act as a ligand by means of carboxylate and amino groups for the crucial metal ions in biological processes.[3] The studies on aspartame and its metal complexes have attracted increasing interest in recent years.[1,3–13] Although the spectroscopic and thermal characterization of synthesized Cu(II)–aspartame complex was carried out in our previous work,[14] no voltammetric studies about the aspartame and its metal complexes were reported in the literature. Voltammetry ensures important information on the interactions of the ligands with the metal ions.[15–18]

In the present study, the voltammetric behaviours of aspartame in the presence and absence of Cu(II), Ni(II) and Zn(II) ions were reported.

2. Results and discussion

2.1. The voltammetric behaviours of aspartame

Aspartame has two ionizable groups, both on the aspartic residue (Scheme 1). At neutral pH in water, both functional groups are ionized. It is well known that aspartame in the buffer solutions was most stable over the pH range 4–5, becoming less stable as the pH increased or decreased.[9] Therefore, for the voltammet-

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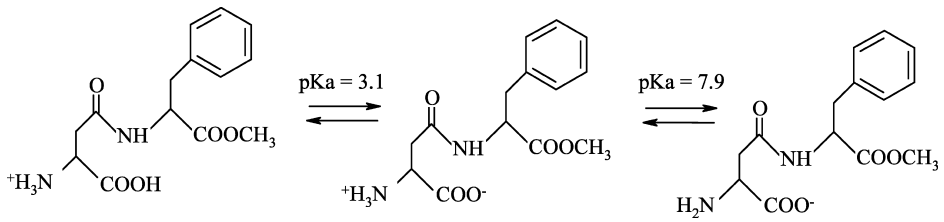


Scheme 1. Molecular structure and pK_a values of aspartame.

ric studies, 0.1 M KF + 0.001 M KCl (pH 5) supporting electrolyte was selected. The selected pH value is also close to the isoelectric point (5.2). The voltammetric behaviour of aspartame in the absence of metal ions (Cu(II), Ni(II), Zn(II)) is shown in Fig. 1. As can be seen in Fig. 1, aspartame gives one reduction peak at − 1.06 V. The nature of the electrochemical process was studied by cyclic voltammetry. When the potential was scanned at increasing rates from 25 to 500 mV s^{-1}, at the cyclic voltammograms under the experimental conditions, a linear relationship was observed between the peak intensity of the reduction process (i_p) and the scan rate (v) (i_p (nA) = 2.866v (mV s^{-1}) + 2.504r = 0.995 (Fig. 2)), suggesting the adsorption of aspartame on the electrode surface. The reduction process was not accompanied by anodic peak which indicates that the redox reaction is totally irreversible (Fig. 1). The peak at − 1.06 V can be used for analytical purposes.

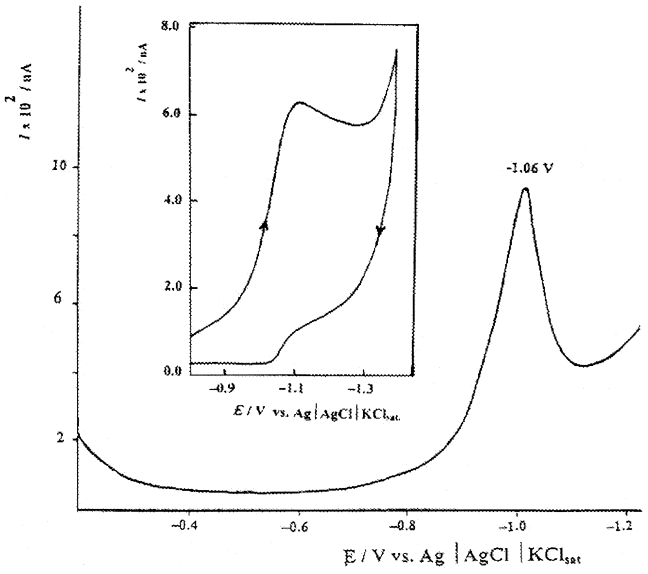


Fig. 1. Square-wave voltammograms of 1×10^{-4} M aspartame solution at 0.1 M KF + 0.001 M KCl (pH 5) supporting electrolyte. Inset: cyclic voltammograms of 2×10^{-3} M aspartame solution at 0.1 M KF + 0.001 M KCl (pH 5) supporting electrolyte. Experimental conditions: pulse height, 20 mV; frequency, 100 Hz; drop size, medium; scan rate, 200 mV s^{-1}; and equilibrium time, 5 s.

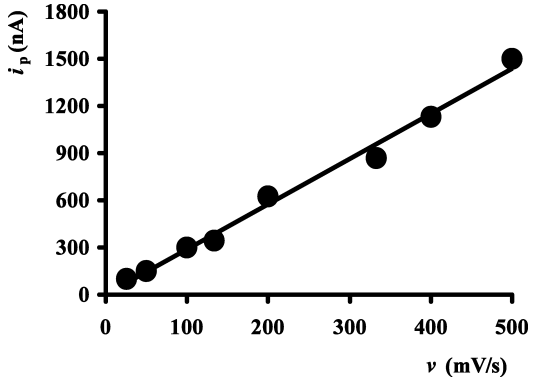


Fig. 2. The dependence of the peak intensity of the reduction process of aspartame (i_p) on the scan rate (v).

2.2. Aspartame in the presence of Cu(II) ions

2×10^{-4} M Cu(II) ions gave a reversible peak with two electron reaction at − 0.115 V in 0.1 M KF + 0.001 M KCl (pH 5) supporting electrolyte (Fig. 3). When aspartame was added to the 2×10^{-4} M Cu(II) solution, over the potential range of 0.150 to − 0.700 V, two quasi-reversible peaks at 0.054 and − 0.186 V and one irreversible peak at − 0.322 V were observed (Fig. 3). The peaks at 0.054 and − 0.186 V are inferred from the two-stage reduction of Cu(II) ions in the presence of the ligand. The peak at − 0.322 V can be attributed to Cu(II)–aspartame (Cu(II)L_2) complex. The similar results were obtained by using square-wave voltammetry technique (Fig. 4).

As can be seen in Figs. 3 and 4, aspartame forms the complexes of both Cu(I) and Cu(II) ions. The observation of two-stage reduction (Cu(II) ⇄ Cu(I) and Cu(I) ⇄ Cu(0)) of copper ions depends on the structure of the ligand.[19] The structural features of the ligand–copper complexes are not immediately clear.[20] However, the stabilization of Cu(I) species may also be due to d–π interactions between the copper d-orbitals and the aromatic π-system rather than the binding of the metal with the carboxylate group.[21]

With increasing the aspartame concentration, the peak current of third peak (− 0.322 V) increases while those of first and second peaks decrease. It is the sign that the concentration of Cu(II)L_2 increases.

From the voltammetric data the electrode mechanisms of these peaks can be suggested as follows:

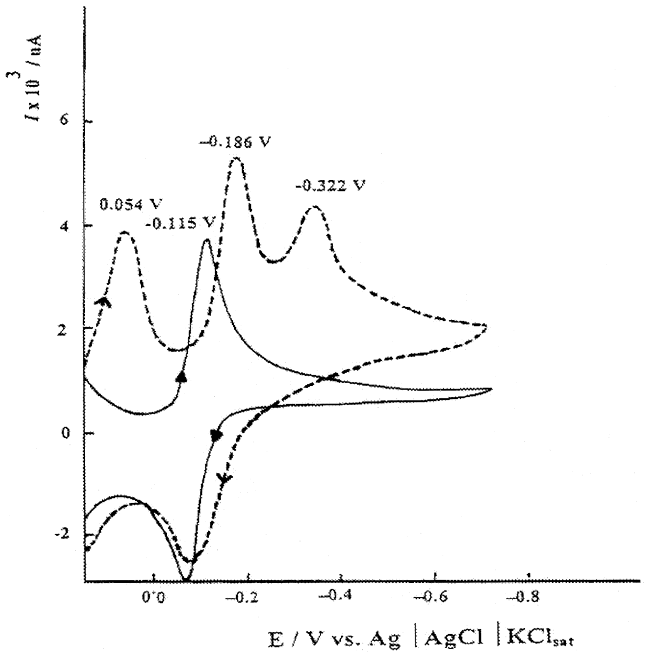


Fig. 3. Cyclic voltammograms of 2×10^{-4} M $CuCl_2$ solution (—); 1×10^{-3} M aspartame solution containing 2×10^{-4} M Cu(II) (---) at 0.1 M KF + 0.001 M KCl (pH 5) supporting electrolyte. Scan rate, 500 mV s^{-1} and other conditions as in Fig. 1. −0.054 V, $Cu(II)L + e^- \rightleftarrows Cu(I)L$; −0.186 V, $Cu(I)L + e^- \rightleftarrows Cu(Hg) + L$; −0.322 V, $Cu(II)L_2 + 2e^- \rightarrow Cu(Hg) + 2L$.

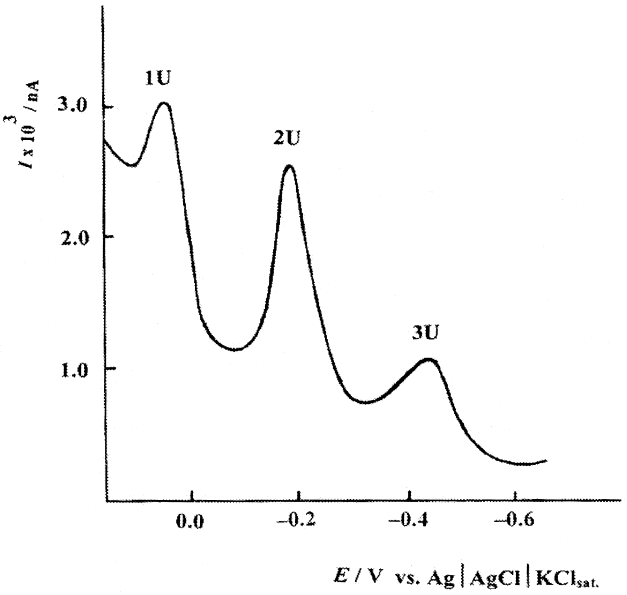
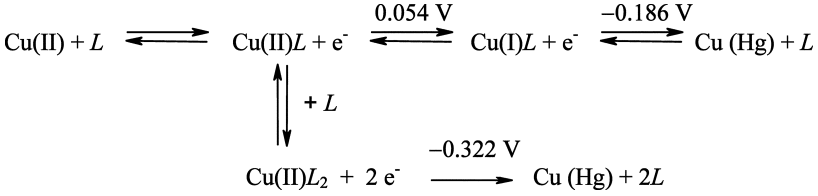


Fig. 4. Square-wave voltammogram of 5×10^{-4} M aspartame solution containing 1×10^{-5} M Cu(II) at 0.1 M KF + 0.001 M KCl (pH 5) supporting electrolyte. Other conditions as in Fig. 1. 1U, $Cu(II)L + e^- \rightleftarrows Cu(I)L$; 2U, $Cu(I)L + e^- \rightleftarrows Cu(Hg) + L$; 3U, $Cu(II)L_2 + 2e^- \rightarrow Cu(Hg) + 2L$.

2.4. Aspartame in the presence of Ni(II)

The square-wave voltammogram of 2×10^{-4} M $NiCl_2$ solution in the absence of aspartame produces a cathodic peak at −1.088 V at pH 5 (Fig. 7). The peak at −1.088 V was inferred from irreversible reduction of the hydrated Ni(II) ions (Fig. 8). Addition of aspartame to 2×10^{-4} M Ni(II) solution led to a decrease in the peak current of the hydrated Ni(II) ions and the formation of a shoulder at positive potential than that of hydrated Ni(II) ions. With increasing aspartame concentration, the potentials of this shoulder is shifted towards more positive potential and fixed at −0.87 V (Fig. 7). The shape of this shoulder is well defined at −0.87 V. Similar results were obtained by the cyclic voltammetry experiments. In the cyclic voltammogram (Fig. 8), with increasing aspartame concentration, a new peak (Fig. 8, 2U) is seen at more positive potential than that of the hydrated Ni(II) ions (Fig. 8, 1U) due to probably the complex formation.

With the addition of increasing concentration of a ligand, the reduction peak potential of metal ion generally shifts to more negative potentials. The reduction of the complexed metal ion is difficult because metal ion is



where L = aspartame.

2.3. Aspartame in the presence of Zn(II)

The square-wave voltammogram of 1×10^{-4} M $ZnCl_2$ in the absence of ligand, gives one peak at −1.1 V due to the reduction of free Zn(II). After adding aspartame into the cell containing 1×10^{-4} M Zn(II), the new irreversible cathodic peak at −1.32 V is observed (Fig. 5). With increasing aspartame concentration, the peak current of free Zn(II) ions at −1.1 V decreases while that of the peak at −1.32 V increases (Fig. 5). The similar results were observed at cyclic voltammograms (Fig. 6).

According to the obtained data, the peak at −1.32 V can be attributed to the reduction of Zn(II)–aspartame complex. As can be also seen in Figs. 5 and 6, the reduction peak of Zn(II)–aspartame complex was only detected at the excess aspartame concentration ([Aspartame]/[Zn(II)] ≥ 20:1).

stabilized by complex formation. However, the reduction of hydrated Ni(II) ions has a large overpotential, the addition of a ligand can reduce the overvoltage and the reduction occurs at more positive potentials than that of the aquaion. This case generally forms at the chelate complexes of Ni(II) ions with nitrogen contained ligands like NH_3, pyridine or aminosugars.[22] In addition, the presence of the coordinating carboxylate group in the ligand molecule diminishes the positive shift.[22] On the other hand, according to the well known rules,[23] the high asymmetry of the coordination of the coordination sphere induced by the first ligand-molecule enhances the electron transfer rate constant.

Finally, the irreversible peak which is more positive potential (-0.87 V) than that of the hydrated Ni(II) ions (-1.088 V) originates from the catalytic reduction of complexed Ni(II) with aspartame.

2.5. Spectroscopic measurements

To compare the stabilities of the complexes of aspartame with Cu(II), Zn(II) and Ni(II) ions, the electronic spectra studies were carried out. The stability constants and stoichiometries of the complexes were determined

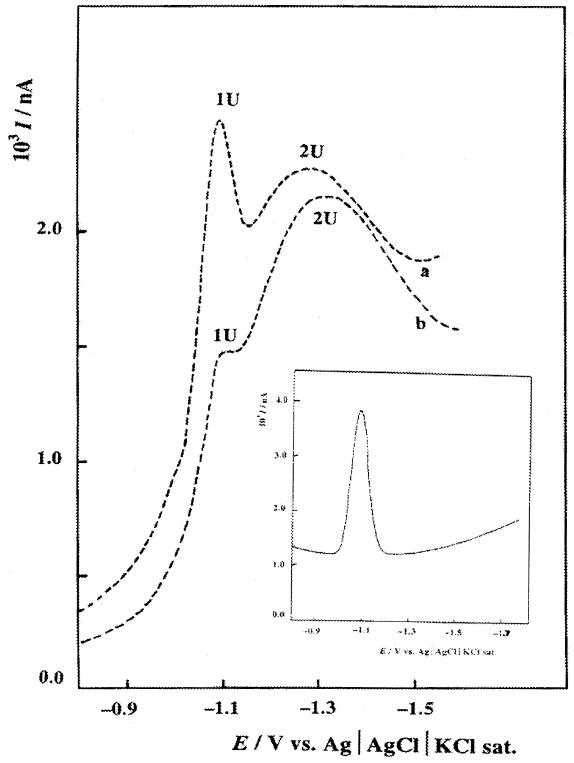


Fig. 5. Square-wave voltammograms of 1×10^{-4} M $ZnCl_2$ solution in the presence of: (a) 3×10^{-3}; (b) 6×10^{-3} M aspartame (---) at 0.1 M KF + 0.001 M KCl (pH 5) supporting electrolyte. 1U, the reduction of free Zn(II); 2U, the reduction of Zn(II)–aspartame complex. Inset: square-wave voltammograms of 1×10^{-4} M aspartame solution at 0.1 M KF + 0.001 M KCl (pH 5) supporting electrolyte. Other conditions as in Fig. 1.

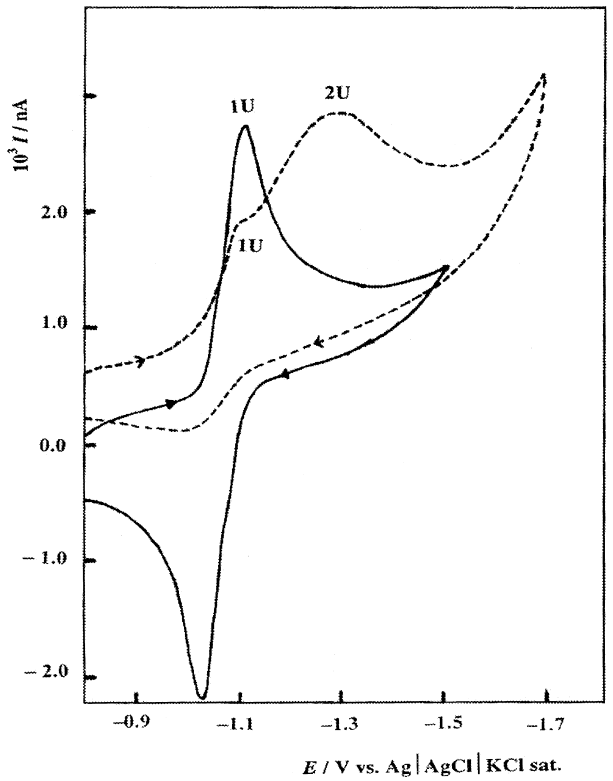


Fig. 6. Cyclic voltammograms of 1×10^{-4} M Zn(II) solution (—); 1×10^{-4} M Zn(II) solution containing 6×10^{-3} M aspartame at 0.1 M KF + 0.001 M KCl (pH 5) supporting electrolyte (---). 1U, the reduction of free Zn(II); 2U, the reduction of Zn(II)–aspartame complex. Scan rate, 500 mV s^{-1} and other conditions as in Fig. 1.

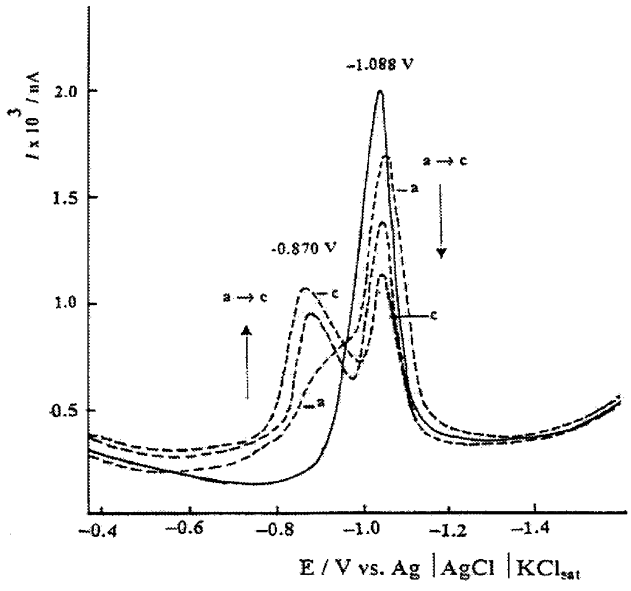


Fig. 7. Square-wave voltammograms of 2×10^{-4} M $NiCl_2$ solution (—); in the presence of: (a) 2×10^{-5}; (b) 1×10^{-4}; (c) 2×10^{-4} M aspartame (---) at 0.1 M KF + 0.001 M KCl (pH 5) supporting electrolyte. Other conditions as in Fig. 1.

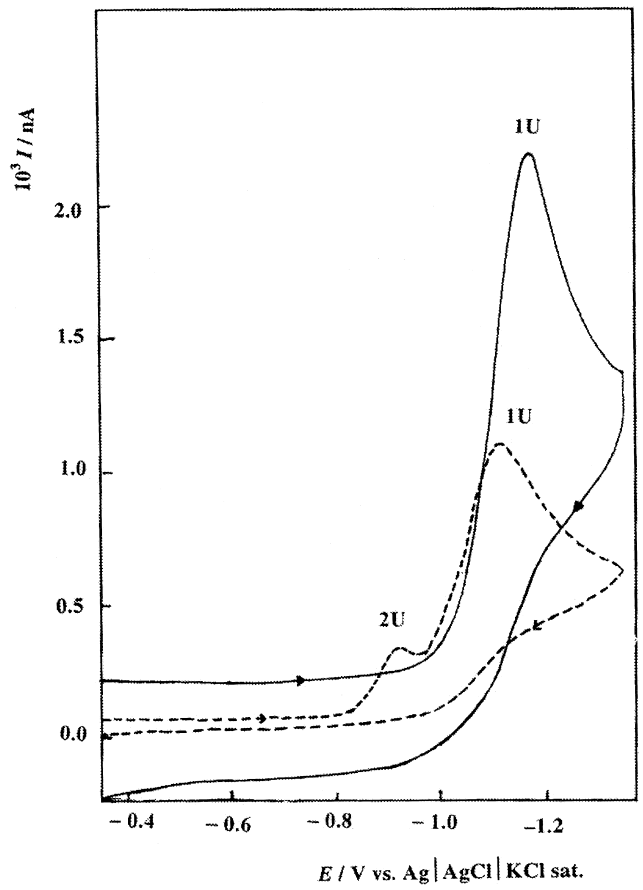


Fig. 8. Cyclic voltammograms of 1×10^{-4} M Ni(II) solution (—); 1×10^{-4} M Ni(II) solution containing 1×10^{-3} M aspartame (---) at 0.1 M KF + 0.001 M KCl (pH 5) supporting electrolyte. 1U, hydrated Ni(II); 2U, Ni(II)–aspartame complex. Scan rate, 500 mV s^{-1} and other conditions as in Fig. 1.

by Job's method. Aspartame and its metal complexes show several absorption maxima in the UV–Vis region. The positions of the absorption band and stability constants of aspartame and its complexes were given in Table 1. As can be seen in Table 1, the UV absorptions bands (Band I) of the complexes can be assigned to the metal–ligand charge transfer bands while their absorptions (Band II) in the visible region are attributed to the d–d transitions. From electronic spectra data of the complexes, their stoichiometries of 1:2 (metal–ligand) in aqueous medium are determined. Although the stabilities of the complexes are different from the found values[3] by means of potentiometric titration (Table 1), they are agreement with Irwing–Williams series (Ni < Cu > Zn).[24]

3. Experimental

3.1. Instrumentation

All experiments were performed with an EG&G PAR Model 384B polarographic analyzer connected to an EG&G PARC Model 303A polarographic stand (Princeton, NJ, USA). A mercury electrode (SMDE working electrode) and an $Ag/AgCl/KCl_{satd}$ reference electrode were used. The auxiliary electrode was a Pt wire. The voltammograms were recorded with a Houston Instrument DMP-40 plotter (Austin, TX, USA).

Electronic spectra were recorded on Unicam V2-100 UV–Vis spectrophotometer in the 800–200 nm range at 1 cm cell length.

3.2. Reagents and solutions

All reagents were of analytical grade. Stock standard solutions were prepared fresh every day in ultrapure triply distilled and deionized water and protected from light and air. Solutions with lower concentrations were prepared by dilution with deionized triply distilled water and were used within a few hours. 0.1 M KF + 0.001 M KCl solution was used as the supporting electrolyte. The pH of the supporting electrolyte was adjusted to 5 by means of HCl soln.

3.3. Procedures

3.3.1. Voltammetry. Before each measurement the solutions were deaerated by a stream of pure nitrogen.

Table 1
Electronic absorption spectra of aspartame and its complexes

Compound	λ_{max}		log β	M(II):L ratio	log β (Ref. 3)
	Band I	Band II			
Aspartame	257				
Cu(II)–aspartame complex	272	420	7.49	1:2	10.84 [a]
Ni(II)–aspartame complex	322	582	6.52	1:2	8.26 [a]
Zn(II)–aspartame complex	261		3.70	1:2	

[a] Potentiometric titration data under physiological conditions ($I = 0.15$ M NaCl in water, 37 °C) M(II) = Cu(II), Zn(II) and Ni(II); L = aspartame.

During the measurements, nitrogen was passed above the solutions in the cell. A known volume of a standard solution of the metal ions was added to the voltammetric cell, which was closed, deaerated, and blanketed with oxygen-free nitrogen. The addition of aspartame to the cell containing the metal ions and vice-versa were carried out and the voltammograms were recorded. All experiments were carried out at ambient temperature (approx 20 °C). The potential scans were recorded using the square-wave and cyclic voltammetry modulations and the following optimum parameters (if not stated otherwise): pulse height, 20 mV; frequency, 100 Hz; drop size medium and equilibrium time 5 s. Each measurement was carried out on a fresh mercury drop.

3.3.2. Spectroscopy. The spectra of mixtures with ambient mole ratio of both metal chlorides and aspartame aqueous solutions were recorded, following the changes in absorbance at the wavelength of maximum absorption.

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