

New complexanes

XLV. Preparation and study of the complex formation of ethylenediamine-*N,N'*-bis(carboxymethyl)-*N*-methylphosphonic acid

P. BUTVIN, I. VALÁŠKOVÁ, M. KOTOUČEK, and J. MAJER

*Department of Analytical Chemistry, Faculty of Pharmacy,
Komenský University, CS-832 32 Bratislava*

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The study of various complexanes possessing carboxymethyl and methylphosphonic groups is described in a number of papers. A new compound of this type is ethylenediamine-*N,N'*-bis(carboxymethyl)-*N*-methylphosphonic acid (EBKMP) prepared by reaction of the Mannich type, and its composition and structure is discussed basing upon the results of elemental analysis, IR, ^1H and ^{13}C NMR spectroscopy. The complex formation of that new agent with series of divalent and trivalent cations was investigated by means of the paper electrophoresis. It was found that this ligand forms complexes of $[\text{MHL}]^-$ and $[\text{ML}]^{2-}$ type (rarely of $[\text{MH}_2\text{L}]^0$) with divalent cations, and those of $[\text{MHL}]^0$, $[\text{ML}_2]^-$, and $[\text{M}(\text{OH})\text{L}]^{2-}$ with the trivalent ones. A procedure for separation of the cation mixture in the presence of ligand in question was worked out.

В ряде работ изучены различные комплексоны, содержащие карбоксиметильные и метилфосфониевые группы. Следующим соединением этого типа является этилендиамин-*N,N'*-бис(карбоксиметил)-*N*-метилфосфониевая кислота, полученная по реакции Манниха. Обсуждается ее состав и структура на основе результатов элементарного анализа, ИК, ^1H ЯМР и ^{13}C ЯМР спектров. Методом электрофореза на бумаге исследовано образование комплексов нового реагента с рядом двух- и трехвалентных катионов. Найдено, что образуются комплексы типа $[\text{MHL}]^-$ и $[\text{ML}]^{2-}$ (иногда $[\text{MH}_2\text{L}]^0$) с двухвалентными катионами и $[\text{MHL}]^0$, $[\text{ML}_2]^-$ и $[\text{M}(\text{OH})\text{L}]^{2-}$ с трехвалентными. Разработан принцип деления смеси катионов в присутствии реагента.

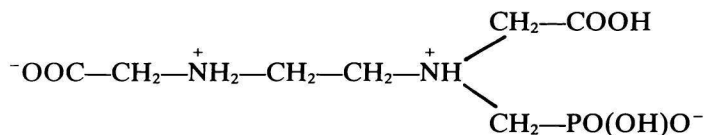
This paper deals with the preparation and study of a new ligand of diamine type recognized as ethylenediamine-*N,N'*-bis(carboxymethyl)-*N*-methylphosphonic acid (EBKMP).

Papers [1, 2] describe the study of the nitrilotriacetic acid derivatives, e.g. ligands of monoamine type, in which the carboxymethyl groups are partly replaced by the methylphosphonic ones. With regard to the results obtained by studying

the chelate formation of glycine-*N,N*-dimethylphosphonic acid (GDP) and *N*-methylphosphonic-iminodiacetic acid (MPIDA) this study was extended also to the ligands of diamine type. Their fundamental representative is ethylenediamine-*N,N'*-bis(carboxymethyl)-*N,N'*-bis(methylphosphonic) acid (EBKBP), which was synthesized for the first time by *Kabachnik* [3]. Its chelating properties were investigated by several authors [3—5].

The new ligand EBKMP was surprisingly the only product of the Mannich type reaction [6] involving ethylenediamine-*N,N'*-diacetic acid, formaldehyde, and phosphorous acid. The composition and structure of EBKMP was evaluated from the results of elemental analysis, IR spectroscopy, and ^1H and ^{13}C NMR spectroscopy. The complex formation with series of divalent and trivalent cations was studied by means of the paper electrophoresis method.

The structure of EBKMP as supposed is



Experimental

Synthesis of EBKMP

9 g (0.05 mol) of ethylenediamine-*N,N'*-diacetic acid (EDDA) (supplied by Fluka, A.G.) were dissolved in 20 cm³ of water in the three-necked round-bottom flask equipped with a stirrer, reflux condenser, and dripping funnel. 5 g (0.05 mol) of 92 mass % phosphorous acid in 10 cm³ of water and 20 cm³ of concentrated hydrochloric acid were added to EDDA solution. The reaction mixture was heated up to boil (120—121 °C) and 8 cm³ (0.1 mol) of 37.2 mass % of aqueous formaldehyde were added dropwise during 1 h. The reaction time was prolonged to 3 h, then the mixture was cooled and evaporated at reduced pressure until a sirupy substance was obtained. Procedure of the evaporation was repeated twice after adding 50 cm³ of water to sirupy-like mixture. Finally it was dissolved in 50 cm³ of 60 volume % of ethanol yielding 11.6 g (85 mass %) of compound regarded as EBKMP, after recrystallization from 60 volume % of ethanol, m. p. = 226—227.5 °C, for C₇H₁₅N₂O₇P (*M_r* = 270.18) *w_i*(calculated): 31.12 % C, 5.59 % H, 10.37 % N, 11.46 % P, *w_i*(found): 31.08 % C, 5.55 % H, 10.25 % N, 11.38 % P. Phosphorus was determined according to Ref. [7].

IR, ^1H and ^{13}C NMR spectroscopy

IR spectra were measured on Perkin—Elmer 377 model in the range of 4000—400 cm⁻¹. The spectrophotometer was calibrated with polystyrene foil. Spectra of EBKMP and its

deuterio derivative were measured in the form of KBr pellets (2 mg/400 mg KBr) using a KBr pellet as reference. *N*-deuterio derivative of EBKMP was obtained by repeated crystallization from D₂O.

¹H NMR spectrum was measured on Jeol FX-100 at 100 MHz, ¹³C NMR spectrum on Jeol FX-60 FT-NMR at 35.3 kHz/4000 Hz by pulse technique. The EBKMP sample was measured as the 10 mass % solution in D₂O. The pH was adjusted to pD = 12 (NaOD) and sodium 3-(3-methylsilyl)propionate was used as an internal standard in ¹H NMR measurements. 1,4-Dioxan served as internal standard in ¹³C NMR measurements. All the measurements were performed at room temperature.

Paper electrophoresis

The experimental procedure as well as the manner of evaluation of the electrophoretographs is described by *Jokl* [8, 9]. The stock electrolytes contained the agent under study with $c = 2 \times 10^{-2}$ mol dm⁻³. Solutions of the metal ions (all as nitrates) were sampled onto chromatographical paper Whatman 2. Their concentrations were 5×10^{-2} mol dm⁻³.

Results and discussion

The preparation of EBKMP, as described, is quick and simple. Originally we have attempted to obtain the EBKBP by this type of reaction, because its synthesis according to *Kabachnik* [3] enables to gain very low overall yields of the desired product and it consumes much of time and labour. Despite the modification of the reaction conditions (mole ratios $n(\text{EDDA}):n(\text{phosphorous acid}):n(\text{formaldehyde})$ were 1:2:4, 1:3:4, 1:3:6, 1:2:2, and 1:1:2; the duration of reaction 2 h, 4 h, and 8 h; the reaction temperatures 100 °C, boil at approx. 120 °C, and 150 °C at pressure in an autoclave) we have always obtained another compound than the desired EBKBP. This substance was first identified as EBKMP according to the results of elemental analysis; the best results were obtained when the equimolar amounts of EDDA and phosphorous acid were reacted with 100 mole % excess of aqueous formaldehyde.

There may exist several reasons for formation of the monomethylphosphonic derivative of EDDA only. One of them could be the steric hindrances of attachment of the second methylphosphonic group to EBKMP being once formed. This hypothesis was supported by modelling the EBKMP molecule with the aid of Dreiding and Calote models, respectively, together with the successful synthesis of 1,3-propanediamine-*N,N'*-bis(carboxymethyl)-*N,N'*-bis(methylphosphonic) acid [10], in which the alkyl chain between the amine nitrogen atoms is extended when compared with EBKMP or EBKBP. The other possible reason may be due to the cyclization of EDDA (after *N*-substitution to the first step), forming thus 2-oxopiperazine derivative. A phenomenon of cyclization has been observed in some cases involving di- and triacetic acids, respectively [11–13].

The composition and structure of EBKMP was further studied by elemental analysis, IR, ^1H and ^{13}C NMR spectroscopy.

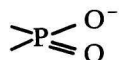
The wavenumbers of characteristic vibrations observed in the IR spectrum are reported in Table 1. The interpretation of that spectrum confirms the betaine

Table 1
Wavenumbers of the absorption bands of vibrations in the EBKMP molecule

Assignment	$\tilde{\nu}/\text{cm}^{-1}$	Assignment	$\tilde{\nu}/\text{cm}^{-1}$
ν_s of (NH_2) and (NH) ⁺	2400—3000	$\nu(\text{P}=\text{O})$ in PO_3H^-	1210
$\nu_{\text{as}}, \nu_s(\text{CH}_2)^*$	3010, 2970	$\nu_{\text{as}}(\text{PO}_2)$ in PO_3H^-	1170
$\nu(\text{CO})$ in $-\text{COOH}$	1740	$\nu_{\text{as}}(\text{P}-\text{O})$ in $\text{P}-\text{O}-\text{H}$	1055
$\nu_{\text{as}}(\text{COO}^-)$	1650	$\nu_s(\text{P}-\text{O})$ in $\text{P}-\text{O}-\text{H}$	930

* — absorption bands in the *N*-deuterio derivative spectrum.

structure of EBKMP, whereas the broad absorption band in the region $\tilde{\nu} = 2400\text{—}3000\text{ cm}^{-1}$ is regarded as the common region of ν_{as} and ν_s vibrations of $-\overset{+}{\text{N}}\text{H}_2-$ and $-\overset{+}{\text{N}}\text{H}-$ groups. The correctness of this assignment was confirmed by inspection of the spectrum of the *N*-deuterio derivative of EBKMP, in which the overlapped bands of ν_{as} and $\nu_s(\text{CH}_2)$ vibrations were detectable due to the shift of former wide absorption band to lower wavenumbers. In the region of absorption of the carboxylate group vibrations there is a band of stretching vibration $\nu(\text{CO})$ of nonionized group and also the one of $\nu_{\text{as}}(\text{COO}^-)$. It means that quaternization of one amino-nitrogen atom is provided by carboxylate group, and the second one is quaternized by the methylphosphonic group. Presence of the ionized phosphonic group may be identified according to [14, 15], basing upon the intensive absorption band with two separated peaks at $\tilde{\nu} = 1210\text{ cm}^{-1}$ and 1170 cm^{-1} regarded as the overlap of $\nu(\text{P}=\text{O})$ and $\nu_{\text{as}}(\text{PO}_2)$ vibrations, coming from the arrangement



The maximum of $\nu_s(\text{PO}_2)$ vibration is at $\tilde{\nu} = 1080\text{ cm}^{-1}$, and presence of the $\text{≡P}-\text{OH}$ fragment of ionized phosphonic group is confirmed by ν_{as} and $\nu_s(-\text{P}-\text{O}^-)$ vibrations, respectively.

^1H NMR spectrum (Fig. 1) is composed of five groups of signals. Basing upon the integral curve (not drawn) and upon the chemical shift rules for the signals of nonlabile protons [16], the assignment of the resonance signals to protons in EBKMP was performed. Thus doublet with a centre at $\delta_r = 2.95\text{ ppm}$ with coupling constant $J_{\text{H}-\text{P}} = 11.96\text{ Hz}$ was assigned to protons (e) of methylene group attached to the $-\text{PO}(\text{OH})\text{O}^-$. Two multiplets with the centres at $\delta_r = 3.35\text{ ppm}$ and

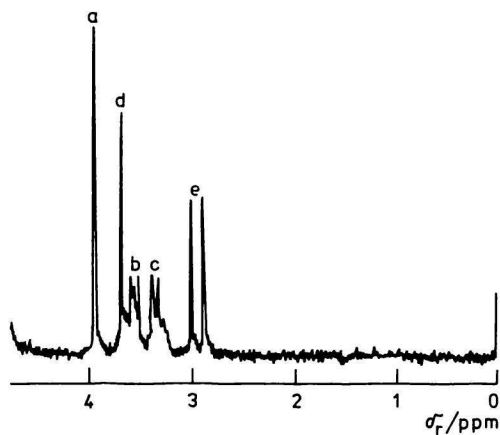


Fig. 1. ^1H NMR spectrum of EBKMP in D_2O , $\text{pD} = 12$ (NaOD), $\theta = 20^\circ\text{C}$.

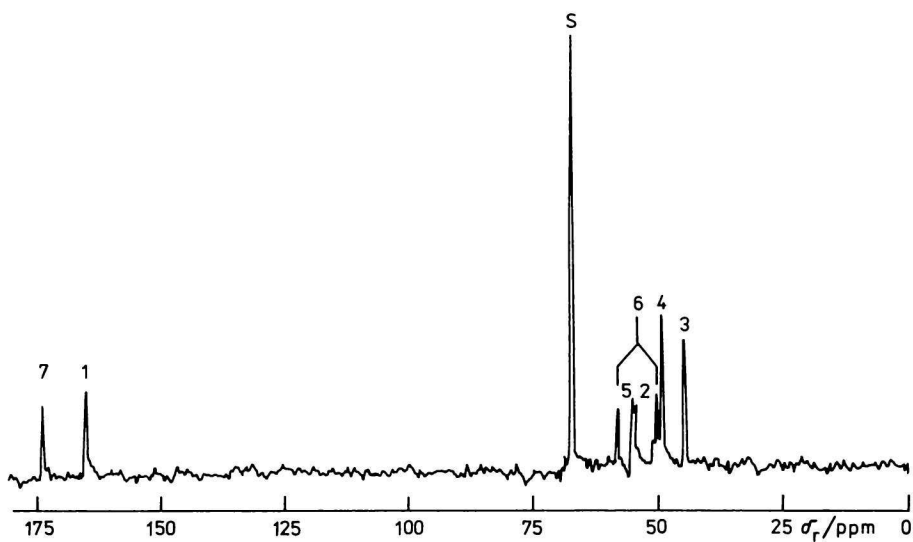
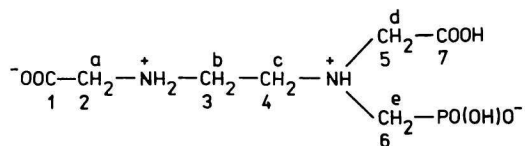


Fig. 2. ^{13}C NMR spectrum of EBKMP in D_2O , $\text{pD} = 7$, $\theta = 20^\circ\text{C}$.



$\delta_r = 3.57$ ppm were assigned to protons (b, c) of methylene groups in ethylenediamine skeleton, respectively. Two singlets at $\delta_r = 3.69$ ppm and 3.97 ppm were assigned to protons (d, a) of methylene groups attached to

the $-\text{COOH}$, respectively. In the case of symmetrical molecule, the spectrum would contain only three groups of signals, whereas the signals of the methylene protons in "ethylenediamine" would reveal the singlet form [17].

^{13}C NMR spectrum (Fig. 2) contains seven resonance signals. The assignment of these signals to seven carbon atoms in EBKMP was performed according to the Adams—Lindenman method [18] (one of the signals is as a doublet with $J_{\text{C-P}} = 116$ Hz) with respect to the bonds of individual carbon atoms.

The interpretation of all the measurements mentioned above, however, does not allow to answer unambiguously the question, whether in the case of EBKMP one may expect the cyclic or noncyclic structure. When assuming the cyclization of proposed EBKMP structure to 2-oxopiperazine derivative after an elimination of water, it would, however, lead to the changes in the number of dissociable protons and thus to changes of acid-base properties and charges of metal chelates of cyclized EBKMP. The results of electrophoretic study, mainly those obtained with trivalent cations, do not confirm the phenomenon of cyclization.

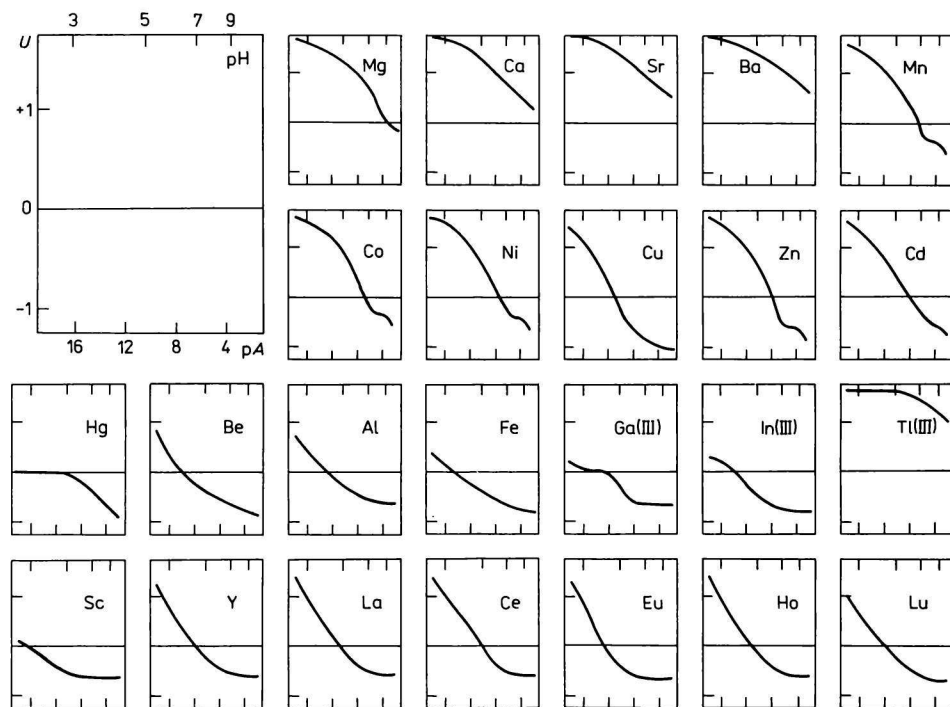


Fig. 3. Electrophoretic mobilities of EBKMP complexes: A — concentration of the free ligand; U — real electrophoretic mobility relative to $(\text{C}_2\text{H}_5)_4\text{N}^+$, ($U = +1.00$), $\theta = 20$ °C, $I = 0.1$ mol kg^{-1} KNO_3 .

The paper electrophoresis method was used for the study of chelating properties of the new ligand EBKMP. This method enables to gain the fundamental information about the type of complexes formed, their charges, and the pH regions of their existence. Protonization constants of EBKMP, which are necessary for given experiments, were obtained from the potentiometric measurements [19].

Fig. 3 shows the electrophoretic mobility curves for 12 divalent and 12 trivalent cations in the presence of EBKMP. Although the whole group of lanthanides was studied, Fig. 3 contains only some curves for lanthanides due to the similarity of their shape.

Divalent cations

The course of electrophoretic mobility curves for Mn(II), Co(II), Cd(II), Ni(II), and Zn(II) indicates that there proceeds the formation of hydrogen complexes of $[\text{MHL}]^-$ type in the pH range from 7.5 to 9.0. The anodic mobility decreases at $\text{pH} > 9.0$ and hence one may conclude the formation of $[\text{ML}]^{2-}$ complexes. The Cu(II) curve is well developed and in the region of plateau (-1.0) it is in agreement with the theoretical value for mobility of the $[\text{ML}]^{2-}$ complexes. Quite a different course reveals the Hg(II) curve, in which the plateau at zero mobility indicates the existence of dihydrogen complex $[\text{MH}_2\text{L}]^0$, and in the strong alkaline region the formation of $[\text{ML}]^{2-}$ complex is supposed.

The affinity of alkaline earth elements to EBKMP is very low. The Be(II) curve cannot be evaluated unambiguously because of steady increase of the anodic mobility without attainment of a stable value. It might be caused by the formation of polynuclear complexes, which would be in agreement with the facts that some ligands possessing phosphonic functional groups form with Be(II) polynuclear complexes [11, 20].

Trivalent cations

The mobility curves for sub-group of gallium are mutually different to significant extent. Thus Ga^{3+} mobility curve reveals two clearly separated parts, whereas the first one belongs to a neutral complex $[\text{MHL}]^0$ and the second to $[\text{ML}]^-$ in anodic region. In the case of In^{3+} , according to the position of plateau, one may suppose the formation of $[\text{ML}]^-$ and $[\text{M}(\text{OH})\text{L}]^{2-}$ complexes in mutually comparable concentrations. Tl^{3+} cation does not reveal any formation of complexes, and the measured mobility in the whole pH range used is that for the free cation. The plateau on the Al^{3+} mobility curve indicates the $[\text{ML}]^-$ complex formation, in the case of Fe^{3+} the formation of $[\text{M}(\text{OH})\text{L}]^{2-}$ is supposed. Inspecting the lanthanide mobility curves one may conclude the formation of $[\text{ML}]^-$ complexes.

The electrophoretic properties of EBKMP when compared with those of GDP and MPIDA [1, 2] are less suitable for analytical purposes. The reason for this statement are both unsatisfactory differences in electrophoretic mobilities and formation of broad diffusion areas. Regardless of this, it is possible to perform quite successful separation on some cation mixtures in the presence of EBKMP (Fig. 4). An optimum pH region for this purpose seems to be the neutral one around the value of 7.5, in which some of components move as the free cations, while the others as the EBKMP complexes.

Ethylenediamine-*N,N'*-bis(carboxymethyl)-*N*-methylphosphonic acid (EBKMP) represents the next ligand in the row of ligands with carboxymethyl and methylphosphonic functional groups. EBKMP forms metal chelates of moderate stability, but reveals a selectivity in chelation.

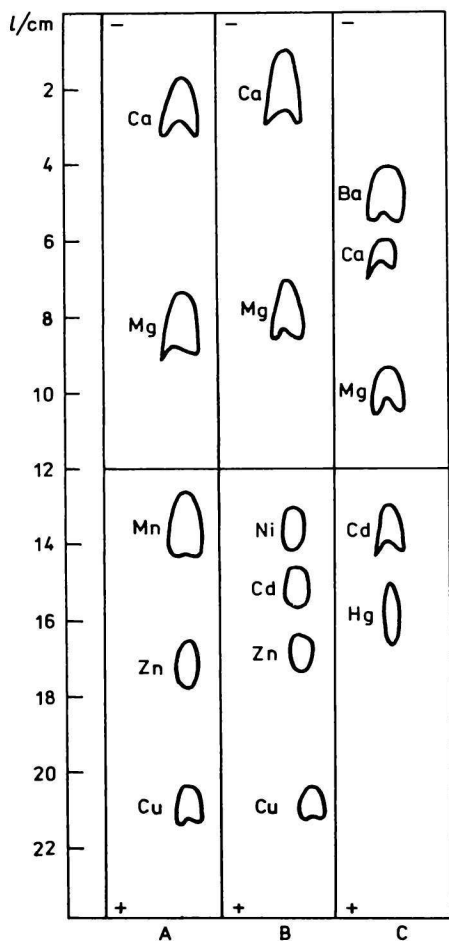


Fig. 4. Electrophoretic separation of metal ions in the presence of EBKMP. Voltage gradient 14 V cm^{-1} , $\theta = 20^\circ \text{C}$, time 1 h. (A, B, C — three types of mixtures.)

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