

REACTIONS OF GUANIDINE POLYMETHACRYLATE WITH ZINC(II) TETRA-4-SULFOPHTHALOCYANINE SODIUM SALT IN AQUEOUS MEDIA

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UDC 544.35:[544.17+544.18]

The interaction of the zinc(II) tetra-4-sulfophthalocyanine sodium salt with guanidine polymethacrylate has been studied by electronic absorption (EAS) and IR spectroscopy and viscosimetry. It was found that the reaction between the macroheterocyclic compound and the polymer proceeds due to the binding of the sulfo groups of metallophthalocyanine and the guanidine cation of the polymer, which leads to an extension of the polymer knot and stabilization of its conformation.

Keywords: immobilization of water-soluble metallophthalocyanines on polymers, zinc(II) tetra-4-sulfophthalocyanine sodium salt, guanidine polymethacrylate, conformation, quantum-chemical calculations, viscosimetry, IR spectroscopy.

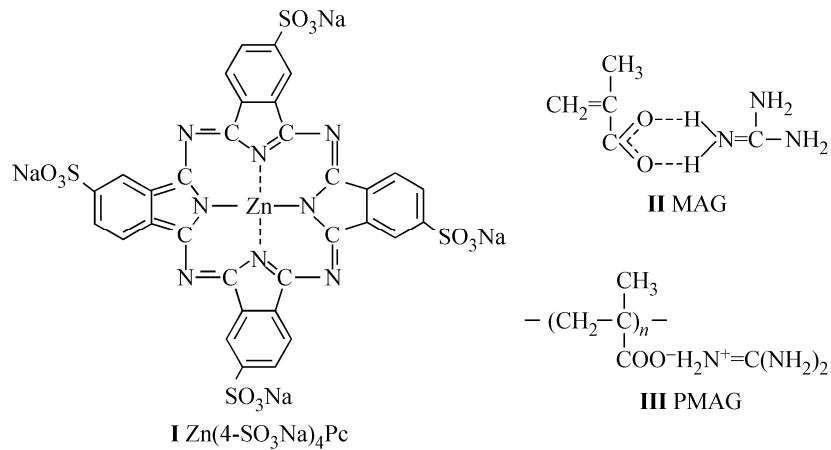
Studies of the interaction between metallophthalocyanines (MPcs) with synthetic and natural polymers is of considerable theoretical as well as practical interest, caused by the development of photosensitizers for photodynamic therapy (PDT) of oncological diseases [1]. The PDT method is based on the ability of chromophore molecules to generate singlet oxygen under the action of light, and oxygen, in turn, oxidizes the biosubstrates [2, 3]. In view of the great importance of photosensitizers, absorbing in the long-wave part of the spectrum and selectively interacting with biopolymers, active research is under way. According to the “SCIRUS” retrieval system, over 7000 scientific publications on photosensitizers appeared in the period from the early 2007 till mid-2008. Among photosensitizers with long lifetimes in the excited triplet state, water-soluble zinc(II) phthalocyanines are especially important. The interactions of these compounds with natural and synthetic polymers have received little or no attention. The goal of this work was to study the interaction of guanidine polymethacrylate (PMAG) with the zinc(II) tetra-4-sulfophthalocyanine sodium salt ($Zn(4-SO_3Na)_4Pc$) in aqueous media and to determine the interaction sites responsible for complexation of $Zn(4-SO_3Na)_4Pc$ with PMAG.

PMAG was chosen as a model compound of proteins and is a polyelectrolyte. Like natural biopolymers, PMAG coagulates in aqueous media when the pH and the ionic strength of the medium changes. MPcs are characterized by active absorption in the long-wave region of the spectrum; the *Q* band of $Zn(4-SO_3Na)_4Pc$ lies at 630 nm. Due to the peripheral (SO_3Na) substituents, zinc(II) phthalocyanine is soluble in aqueous media. The choice of Zn^{2+} (d^{10}) as the central metal ion was dictated by the prolonged lifetime of zinc phthalocyanine complexes in the excited triplet state ($\sigma_{ZnPc} = 245 \mu s$) [4], which allows intermolecular energy transfer that is responsible for the conversion of 3O_2 ($^3\Sigma_g$) into 1O_2 ($^1\Delta_g$) [5].

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EXPERIMENTAL

Objects of study. Zn(4-SO₃Na)₄Pc (**I**, Scheme 1) was synthesized and purified by the standard procedures [6]. The crystalline sample was dried until it ceased to lose weight in vacuum at 343–353 K to remove the solvent molecules. The purity of the substance was controlled according to the electronic absorption spectra (EAS) of Zn(4-SO₃Na)₄Pc in DMF and DMSO, which showed good agreement with the literature data [6]. Guanidine methacrylate (MAG) and PMAG (Scheme 1; **II**, **III**) were synthesized by the procedure of [7]. NaCl of “kh.ch.” (reagent) grade was purified by recrystallization from water and purified in vacuum at 380–390 K. To prepare the solutions, we used twice-distilled deionized water. The concentration of PMAG in aqueous NaCl (0.05 M) was 0.08 wt.%; the concentration of Zn(4-SO₃Na)₄Pc was 0.4 mM.



Scheme 1.

Methods. The EAS of aqueous Zn(4-SO₃Na)₄Pc with MAG additions were measured on a Cary 100 Varian spectrophotometer in the range 200–800 nm. For recording the EAS of the above-mentioned solutions, we used quartz cells 10 mm thick.

The IR spectral studies of the crystalline samples of the individual MAG, PMAG, and Zn(4-SO₃Na)₄Pc and the Zn(4-SO₃Na)₄Pc–PMAG complex were carried out in the range from 4000 cm⁻¹ to 400 cm⁻¹ for KBr on an Avatar 360 FTIR ESP spectrophotometer.

The kinematic viscosity of aqueous solutions containing PMAG, NaCl, and Zn(4-SO₃Na)₄Pc was determined with a capillary viscosimeter; the data were collected and analyzed on a computer. The volume of emanated liquid was 10 ml; the diameter of the capillary was 0.38 mm. The error of the viscosity measurement was 10⁻⁴ mPa·s. The measurements were carried out at 298.15 K. The capillary viscosimeter was calibrated against twice-distilled water at different temperatures (293.15 K, 298.15 K, 303.15 K, and 313.15 K). The resulting values of the kinematic viscosity of water agree well with the literature data [8].

Solutions for studies were prepared by the weight method (Genius scales, series ME); the measurement error was 10⁻⁵ g. To recalculate molal into molar concentration, we measured the density of the corresponding solutions at 298.15 K on a VIP 2M vibration densimeter (Russia) to an error of 10⁻⁴ g/cm³.

RESULTS AND DISCUSSION

Introduction of an electrolyte (NaCl) in an aqueous polymer solution leads to a screening of polyion charges and decreases the electrostatic repulsion between the ionogen groups charged in the same sense, due to which the polyelectrolyte molecule tends to be rotated and acquire a more asymmetric shape compared with the form of the statistical knot. The degree of rotation of the polyion depends on the electrolyte concentration. As is known, the degree of interaction between water

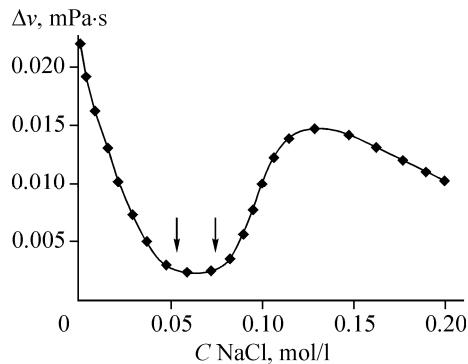


Fig. 1. Dependence of the kinematic viscosity ($\Delta v = v_{\max} - v_{\min}$) of aqueous solutions containing 0.4 mM Zn(4-SO₃Na)₄Pc, 0.08 wt.% PMAG, and NaCl on the concentration of the supporting electrolyte in solution after 160 h.

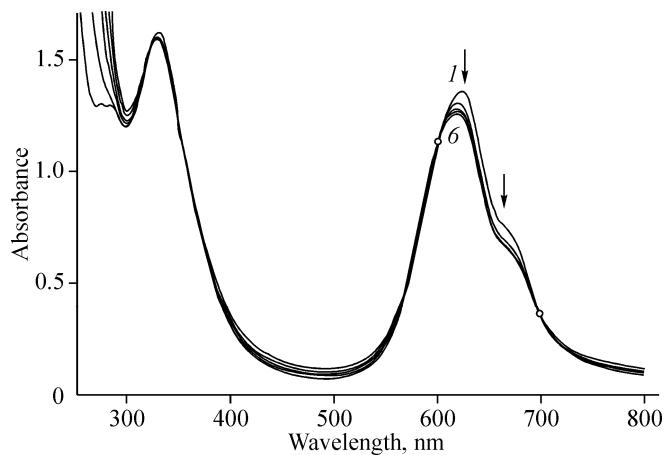
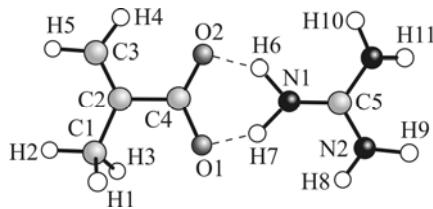


Fig. 2. EAS of the aqueous solution of 0.4 mM Zn(4-SO₃Na)₄Pc with (1) 0.11 mg, (2) 0.25 mg, (3) 0.43 mg, (4) 0.67 mg, (5) 0.82 mg, and (6) 0.92 mg MAG additions.

molecules and the functional groups of a polyelectrolyte, i.e., the degree of hydration of the latter, is a factor that is largely responsible for its main physicochemical parameters and, primarily, the conformation of the macromolecule in aqueous solutions. For PMAG, too, water molecules are certainly involved in structure stabilization in such a way that the macromolecule takes the form of a swelled knot, stabilized by hydrogen bonds and hydrophobic interactions. At high concentrations (of the order of 1 M) of the supporting electrolyte, the contribution of Coulomb interactions to the unwinding of polymer chains becomes minimum. Further addition of NaCl to aqueous polymer can lead to salting-out, and the kinematic viscosity of the solution will increase. As any polyelectrolyte, aqueous solutions of PMAG typically show the polyelectrolyte swelling effect, which shows itself in a change in the kinematic viscosity of solutions with time and results from a rearrangement of the local structure of the chain and other conformational changes. To determine the optimum content of the supporting electrolyte that stabilizes the polymer but does not lead to association or aggregation of MPc, we determined the kinematic viscosity of aqueous solutions of PMAG at different NaCl concentrations. The resulting data (Fig. 1) show that the polymer is stabilized in the range 0.05–0.08 mol/l of sodium chloride concentrations. According to the previously obtained data [9, 10], the increased concentration of the supporting electrolyte in solutions favors association of metallophthalocyanine molecules in aqueous media; therefore, 0.05 mol/l was chosen as the optimum concentration of NaCl (from the above-indicated range), and further research was carried out at this concentration.

As mentioned above, MPc molecules are hydrophobic and liable to association in aqueous media [9, 10]. In the general case, self-association of MPc is diffusion-controlled; the time necessary for an equilibrium to set in is 5–6 h [10]. A similar effect was observed for polymers that demanded longer time (~10 h) for solution in aqueous media. Because of this, classic titration, namely, addition of any of the (MPc or polymer) reagents in the crystalline state to the solution of the second reagent is impossible. Therefore, we estimated the spectral signals of the interaction between Zn(4-SO₃Na)₄Pc and the monomer (unit) link MAG. Figure 2 shows the electronic absorption spectra of aqueous Zn(4-SO₃Na)₄Pc with a MAG addition. The changes in the electronic absorption spectra of Zn(4-SO₃Na)₄Pc with a MAG addition were independent of the state of MPc in solution. In the starting solution, Zn(4-SO₃Na)₄Pc was mainly dimerized (the intensity of the Q band of the dimer $\lambda = 631$ nm was much higher than that of the Q band of the monomer $\lambda = 675$ nm). After MAG was added to the solution under study, the intensity of absorption in the visible part of the spectrum decreased. Titration was isobestic in character, which was indicative of the stoichiometric change in the ratio of the interacting substances (Zn(4-SO₃Na)₄Pc and MAG). The addition of MAG evidently does not lead to a shift of the associative equilibrium toward dimerization

(association) because the electronic absorption spectra do not show the absorption of MPc associates of higher orders [11] and the absorption intensity of both monomer and dimer decreases (Fig. 2). Based on the structure of Zn(4-SO₃Na)₄Pc, we can assume that complexation of Zn(4-SO₃Na)₄Pc with MAG/PMAG can result from the predominantly electrostatic interaction of the peripheral substituents of MPc with the charged surface of MAG/PMAG or donor–acceptor interaction between the amino group of MAG/PMAG and the central metal ion. The absence of the charge transfer band at 400–500 nm in the case of coordination of electron-donor ligand to the central metal ion suggests that the interaction between molecules involves the peripheral substituents of MPc.



Scheme 2. Structure and atomic numbering scheme for the MAG molecule.

To determine the interaction centers responsible for the complexation of Zn(4-SO₃Na)₄Pc with PMAG, we carried out IR spectral analysis of the individual PMAG, Zn(4-SO₃Na)₄Pc, and the Zn(4-SO₃Na)₄Pc–PMAG complex. For correct assignment of signals, we performed *ab initio* calculations of the IR spectrum of MAG (Scheme 2) by the DFT/LSDA method (3-21g basis) using the GAUSSIAN-03 program [12]. Our calculations revealed good agreement between the experimental and calculated spectra of MAG (Table 1). It was shown [13] that the major difference between the IR spectra of MAG and PMAG was absorption at 938 cm⁻¹ and 1008 cm⁻¹, which is due to the out-of-plane deformation vibrations CH₂=C. The other bands that are active in the IR spectra of MAG are also present in the IR spectra of PMAG. This allowed us to draw an analogy in band assignment between MAG and PMAG.

A comparative analysis of the IR spectra of the crystalline samples of the individual PMAG, Zn(4-SO₃Na)₄Pc, and Zn(4-SO₃Na)₄Pc–PMAG (Fig. 3) showed that the majority of the bands inherent in the polymer and MPc were preserved for Zn(4-SO₃Na)₄Pc–PMAG. Also, the following changes in the spectra were revealed: 1) the wide band at 2210 cm⁻¹ in the spectrum of PMAG, which defines the asymmetric stretching vibrations of NH₂ of the guanidine fragment in the spectrum of Zn(4-SO₃Na)₄Pc–PMAG vanished; 2) the intense and narrow band at 1400 cm⁻¹ in the spectrum of Zn(4-SO₃Na)₄Pc, which is characteristic for O=S vibrations in the SO₃ substituent [14], was also absent in the spectrum of Zn(4-SO₃Na)₄Pc–PMAG. These changes suggest that the PMAG–Zn(4-SO₃Na)₄Pc complex formed as a result of the interaction of the sulfo groups of Zn(4-SO₃Na)₄Pc with the guanidine fragment of the polymer.

The viscosity of PMAG solutions unexpectedly decreased after the addition of Zn(4-SO₃Na)₄Pc. The viscosity of the corresponding solutions generally increases during immobilization of chromophore molecules on polymers [15], which is associated with an increase in the molecular mass of the polymer. For polyelectrolytes, however, the data showed that the conformation changes caused by the complexation of MPc with the polymer produced greater effect on the hydrodynamic characteristics of the solutions than the increased molecular mass. Immobilization of the metal phthalocyanine molecule on the polymer can take place inside the polymer knot or on its surface. In the former case, the knot conformation will be stabilized, which should increase the viscosity of the solutions; in the latter, when MPc is localized on the surface of PMAG, the kinematic viscosity of the solutions will decrease. A decrease of 2.6% in the kinematic viscosity of the solution of the PMAG complex with MPc (1.0523 mPa·s) compared with the solution of PMAG (1.0802 mPa·s) indicates that immobilization of MPc occurs on the surface of the polymer.

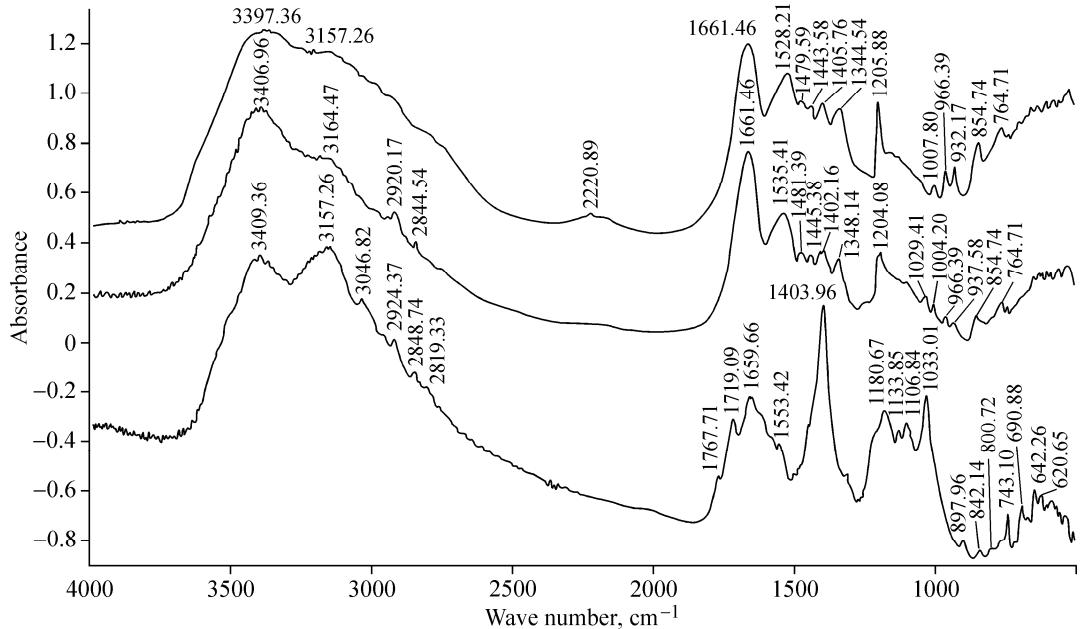


Fig. 3. IR spectra of PMAG (upper line), $\text{Zn}(\text{4-SO}_3\text{Na})_4\text{Pc}$ –PMAG complex (medium line), and $\text{Zn}(\text{4-SO}_3\text{Na})_4\text{Pc}$ (lower line) in KBr pellets.

TABLE 1. Experimental ν_{exp} (cm^{-1}) and Calculated ν_{calc} (cm^{-1}) Frequencies in the IR Spectra of PMAG and MAG

PMAG	ν_{exp}	ν_{calc} of MAG	Types of atomic vibrations*
479	466	472	$\text{N}^{(2)}\text{H}^{(8)}$, $\text{N}^{(2)}\text{H}^{(9)}$ def. $\text{N}^{(3)}\text{H}^{(10)}$, $\text{N}^{(3)}\text{H}^{(11)}$ def.
540	547	546	$\text{N}^{(2)}\text{H}^{(8)}$, $\text{N}^{(2)}\text{H}^{(9)}$ def. $\text{N}^{(3)}\text{H}^{(10)}$, $\text{N}^{(3)}\text{H}^{(11)}$ def.
765	772	749	$\text{C}^{(5)}\text{N}^{(3)}$, $\text{C}^{(5)}\text{N}^{(2)}$ def.
—	938	938	$\text{C}^{(2)}=\text{C}^{(3)}$ str.
967	946	989	$\text{C}^{(5)}\text{N}^{(3)}$, $\text{C}^{(5)}\text{N}^{(2)}$ symm. str.
—	1008	1008	$\text{C}^{(2)}=\text{C}^{(3)}$ str.
1205	1234	1279	$\text{C}^{(1)}\text{C}^{(2)}$ def. $\text{N}^{(2)}\text{H}^{(8)}$, $\text{N}^{(2)}\text{H}^{(9)}$ symm. def. $\text{N}^{(3)}\text{H}^{(10)}$, $\text{N}^{(3)}\text{H}^{(11)}$ symm. def.
1339	1384		$\text{C}^{(1)}\text{H}^{(1)}$, $\text{C}^{(1)}\text{H}^{(2)}$, $\text{C}^{(1)}\text{H}^{(3)}$ symm. def. (umbrella)
1399	1408	1392	$\text{C}^{(4)}\text{O}^{(1)}$, $\text{C}^{(4)}\text{O}^{(2)}$ str.
1480	1456	1482	$\text{C}^{(5)}\text{N}^{(3)}$, $\text{C}^{(5)}\text{N}^{(2)}$ asymm. str.
1658	1653	1622	$\text{N}^{(2)}\text{H}^{(8)}$, $\text{N}^{(2)}\text{H}^{(9)}$ def. $\text{N}^{(3)}\text{H}^{(10)}$, $\text{N}^{(3)}\text{H}^{(11)}$ def.
1942	1682	1699	$\text{N}^{(2)}\text{H}^{(8)}$, $\text{N}^{(2)}\text{H}^{(9)}$ def. $\text{N}^{(3)}\text{H}^{(10)}$, $\text{N}^{(3)}\text{H}^{(11)}$ def. $\text{N}^{(1)}\text{H}^{(6)}$, $\text{N}^{(1)}\text{H}^{(7)}$ def. $\text{C}^{(5)}=\text{N}^{(1)}$ symm. str.
2210	2195	2151	$\text{N}^{(1)}\text{H}^{(6)}$, $\text{N}^{(1)}\text{H}^{(7)}$ asymm. str.
2510	2848	2411	$\text{N}^{(1)}\text{H}^{(6)}$, $\text{N}^{(1)}\text{H}^{(7)}$ symm. str.
3410	3370	3720	$\text{N}^{(1)}\text{H}^{(6)}$, $\text{N}^{(1)}\text{H}^{(7)}$ symm. str.

*Def. — deformation, symm. str. — symmetric stretching, asymm. str. — asymmetric stretching, str. — stretching, and symm. def. — symmetric deformation vibrations.

CONCLUSIONS

1. The EAS and IR spectral studies of the reactions of Zn(4-SO₃Na)₄Pc with PMAG (the model of natural biopolymers) and its MAG unit showed that the interaction of the macroheterocyclic compound and PMAG/MAG proceeds due to the complexation of the sulfo groups of Zn(4-SO₃Na)₄Pc with the guanidine cation of the polymer/monomer.

2. Evaluation of the hydrodynamic parameters of the solutions of the polymer and complexes on its basis in aqueous media confirmed the conclusions drawn from spectral data (immobilization of Zn(4-SO₃Na)₄Pc molecules occurs on the surface of the polymer and leads to the extension of the polymer knot and stabilizes its conformation). For the ultimate purpose of the study it is also important that the fifth and sixth coordination sites of the central metal ion of Zn(4-SO₃Na)₄Pc in the complex remain vacant.

3. For polyelectrolytes, changes in the hydrodynamic characteristics of polymer solutions with metallophthalocyanine additions did not unambiguously suggest complexation between the metallophthalocyanine molecules and the polymer nor its absence.

This work was supported by the Russian Foundation for Basic Research grant No. 08-03-97503-r_tsentra_a.

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