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Polyelectrolyte complexes in solution and in bulk

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Abstract. The review surveys the thermodynamics, kinetics and reaction mechanisms of oppositely charged polyelectrolytes in aqueous solutions giving rise to insoluble stoichiometric or soluble non-stoichiometric interpolyelectrolyte complexes. The mechanisms of polyelectrolyte exchange reactions are discussed. Equilibrated non-stoichiometric interpolyelectrolyte complexes show a dual behaviour in aqueous solutions. On the one hand, they behave as usual linear polyelectrolytes and, on the other hand, they exhibit properties of amphiphilic block copolymers. The addition of low-molecular-weight salts to solutions of interpolyelectrolyte complexes usually leads to redistribution of electrostatically bound chains and phase separation. Analysis of these processes is of key importance in assigning these complexes to a special family of polymeric materials. Selected data on the conformations of polyions in solid interpolyelectrolyte complexes are given and their thermomechanical properties in the swollen state are considered. The bibliography includes 117 references.

I. Introduction

Interpolyelectrolyte complexes (IPECs) belong to a special family of polymeric compounds [1–6] formed through cooperative electrostatic interactions between polycations with polyanions upon mixing of aqueous solutions of oppositely charged polyelectrolytes. Depending on the charge ratio and the degree of polymerisation of the starting polyelectrolytes, either non-stoichiometric water-soluble or stoichiometric insoluble IPECs exhibiting low swelling in water can be prepared.

An analysis of the state of the art in research on IPECs, which was based essentially on the results of investigations performed over many years at the Chair of High-Molecular-Weight Compounds of the Department of Chemistry of the Moscow State University, has been presented recently in the introductory chapter of Ref. 7. This chapter was used as the basis for the present review.

In the 1930s, researchers working in the field of colloidal chemistry found that, under particular conditions, mixing of aqueous solutions of oppositely charged natural polyelectrolytes characterised by a relatively low charge density on the macromolecules (for example, gelatins and gum arabic) leads to phase separation and formation of liquid coacervates.[8–10] Further studies of such systems have been aimed primarily at characterising the conditions of phase separation by experimental and theoretical methods.[11,12]

Solid IPECs exhibiting low swelling in water have also been known for many years. Synthetic polyelectrolytes with a high linear charge density have become available at least from the early 1960s.[1,13–15] Later, the practical use of these compounds has attracted attention. For example, insoluble IPECs proved to be highly efficient as ecologically safe hydrophilic binders, which prevent soil erosion by wind and water. Composites based on such IPECs were used, for instance, for suppressing the formation of radioactive aerosols in the contaminated dusting areas of the Chernobyl disaster. Industrial tests showed that insoluble IPECs are much more efficient than individual polyelectrolytes, which are generally used for coagulation of colloidal dispersions, in particular, of metallurgical slags (see, for example, Ref. 16). Insoluble IPECs were also successfully tested as biocompatible coatings for blood-contacting medical materials (including chemisorbents) and other biological liquids (see, for example, Ref. 17).

There also some other promising fields of application of IPECs. One of them is being extensively developed and deals with the preparation of thin films consisting of alternating nanosize polycation and polyanion layers. These films are prepared by successive deposition of oppositely charged polyelectrolytes from aqueous solutions on various surfaces.[7]

The existence of water-soluble interpolyelectrolyte duplexes was supported by several examples [18,19] and the general conditions and criteria for their formation were revealed, which proved to be valid for most pairs of oppositely charged polyions.[3,5,20,21] These are considerable achievements, which marked the onset of a new stage of investigation of IPECs associated with the possibility of employing all modern physical and physicochemical methods generally used in studies of macromolecules in solution (light scattering, analytical ultracentrifugation, viscosimetry, gel-permeation chromatography, *etc.*). Fundamental data obtained by these methods gave a deeper insight into the structural organisation and behaviour of IPECs not only in solutions but also in the bulk. These investigations also opened new fields of application of IPECs, in particular, in biotechnology, medicine, and modelling of biological systems.[22–26] For example, it appeared that interpolyelectrolyte duplexes involving DNA plasmids or single-stranded antisense oligonucleotides as polyanions can penetrate rather easily through biological membranes analogously to viri-

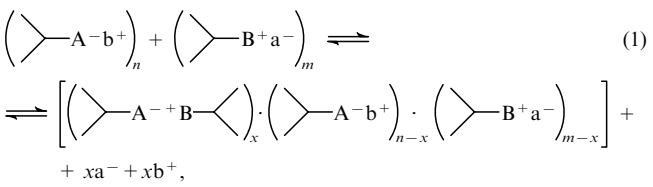
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ons. Nowadays, this phenomenon is used for delivering genetic material to cells to transfect or block specified genome regions.[25]

II. Interpolyelectrolyte reactions and solution behaviour of interpolyelectrolyte complexes

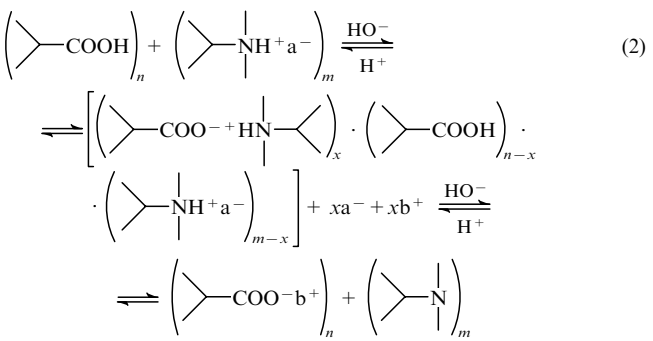
The simplest procedure for the preparation of IPECs involves mixing of two aqueous solutions containing polyanions and polycations, respectively. The reaction of two strong polyelectrolytes can be represented as follows:



(1)

where A^- and B^+ are acidic and basic side groups, respectively, and a^- and b^+ are counterions.

An interaction between two weak polyelectrolytes can be described by the following scheme:



(2)

The degree of conversion Θ in these reactions is determined as the ratio of the number of salt bonds (ion pairs) formed between polyions under particular conditions to their maximum possible number

$$\Theta = \frac{x}{m}, \text{ if } n \geqslant m,$$

and

$$\Theta = \frac{x}{n}, \text{ if } n < m\,.$$

The formation of duplexes from weak polyelectrolytes can be controlled by varying pH of the medium.[3,6] In these cases, IPECs can be prepared in equilibrium conditions by gradual acidification or alkalisation of the reaction mixture.

The degree of conversion Θ can be calculated from the results of potentiometric titration.[3,6]
For a weak polyacid,

$$\Theta = \frac{m_b/V + [H^+] - \sqrt{K_a c_0}}{c_0}, \tag{3}$$

for a weak polybase,

$$\Theta = \frac{m_a/V + [OH^-] - \sqrt{K_b c_0}}{c_0}. \tag{4}$$

In these equations, m_a or m_b are the numbers of moles of the acid or base, respectively, added to the mixture, V is the volume of the reaction mixture, K_a and K_b are the characteristic ionisation constants of the polyacid and the polybase, respectively, and c_0 is the concentration of one of the polyelectrolytes.

Typical plots of Θ *vs.* pH, which were calculated from experimental titration curves of weak polyelectrolytes in the presence of oppositely charged polyions, are shown in Fig. 1. Solid lines enclose the pH region where IPECs are formed and

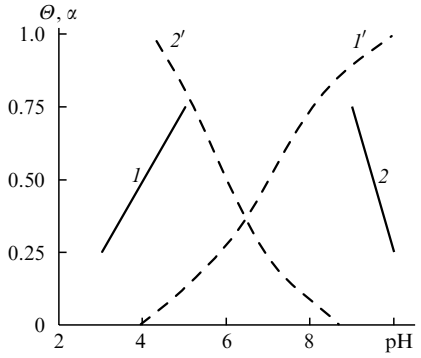


Figure 1. Typical plots of the degrees of conversion (Θ) in reactions of weak polyelectrolytes (*1*, *2*) and their starting degrees of ionisation (α) (*1′*, *2′*) *vs.* pH in aqueous solutions.

exist in the reaction system in the absence of low-molecular-weight salts. If one polyelectrolyte is weak, whereas another polyelectrolyte is strong, the range of existence is limited only by one curve either on the left or on the right, respectively. Figure 1 shows also the plots of the degree of ionisation α of individual polyelectrolytes *vs.* pH. It can be seen that polyacids and polybases whose degree of ionisation depends on pH become much stronger in the presence of oppositely charged polyions.

The value of $\Delta pH(\Theta,\alpha)$ is a measure of the free energy (ΔG_{cs}), which is a driving force for the complexation process. This parameter characterises a cooperative multicentre interaction between the oppositely charged units of polyion chains at $\Theta = \alpha$

$$\Delta pH(\Theta,\alpha) = \frac{\Delta G(\alpha) - \Delta G(\Theta)}{2.3\,RT} = \frac{\Delta G_{cs}(\Theta,\alpha)}{2.3\,RT}. \tag{5}$$

Here $\Delta G(\alpha)$ and $\Delta G(\Theta)$ are the free energies of ionisation of a weak polyelectrolyte in the absence and in the presence of an oppositely charged polyion, respectively.

Equation (3) is written on the assumption that each ionised group of the polyelectrolyte that is titrated forms a salt bond (ion pair) with an oppositely charged polyion. This situation is close to reality if the ratio of the numbers of ionising groups of the components ($Z = m/n$) is equal to unity. For $Z \neq 1$, Eqn (3) is valid if the total number of ionising groups in a weak polyelectrolyte is smaller than that in the fully ionised strong polyelectrolyte.

A decrease in the free energy corresponding to the shift of the equilibria (1) and (2) toward IPECs takes place primarily due to an increase in the entropy caused by release of low-molecular-weight counterions, which are initially localised in the vicinity of polyelectrolyte coils. However, depending on the composition and structure of the oppositely charged polyions, other factors, for example, hydrophobic interactions, hydrogen bonds, charge transfer, *etc.*, can contribute substantially to their coupling.

In terms of the commonly accepted classification, the processes (1) and (2) correspond to the ion exchange and neutralisation reactions, respectively. However, in relation to interacting polyelectrolytes, these processes can be considered as coupling reactions of oppositely charged polyions.

Interpolyelectrolyte complexes can also be prepared by polymerisation of ionic monomers on oppositely charged polyions serving as matrices.[27] In this case, the total change in the free energy includes two terms

$$\Delta G_{tp} = \Delta G_p + \Delta G_{cs}\,, \tag{6}$$

where ΔG_p is the free energy of polymerisation in the absence of a matrix. The negative value of ΔG_{cs} is thermodynamically favourable for the formation of a polymer. This factor may be of decisive importance if polymerisation of a free monomer is thermodynamically impossible ($\Delta G_p > 0$): ΔG_{tp} remains negative if

$|\Delta G_{cs}| > |\Delta G_p|$. In other words, a polyion matrix, being a potential component of IPEC, shifts the polymerisation–depolymerisation equilibrium toward the oppositely charged polyion.

A factor analogous to ΔG_{cs} is responsible for clustering of protein globules with oppositely charged linear polyions upon complexation of polyelectrolytes with proteins[28–30] and for aggregation of ionic surfactants in solutions and hydrogels of oppositely charged polyelectrolytes at surfactant concentrations substantially lower than the critical micelle concentration (CMC).[31–37] In reality, both these processes consist in 'polymerisation' of protein globules or surfactant ions on the oppositely charged polymer matrices.

For a particular structure of polyelectrolytes, the ability of IPEC to dissolve or swell in water depends on Z, Θ, the ratio of the degrees of polymerisation of the oppositely charged polyions and the composition of an aqueous phase (the nature and concentration of low-molecular-weight salts, pH, the presence of organic additives, *etc.*). If $Z = 1$ and Θ is close to unity, the interpolyelectrolyte reaction affords stoichiometric IPECs, which are always insoluble but swell in water to some degree.

Under particular conditions, most pairs of oppositely charged polyelectrolytes give water-soluble IPECs.[3,5,20,21] At $Z = 1$, the solubility of duplexes can be achieved only at $\Theta < 1$, *i.e.*, for products of the incomplete reaction (2).[20] In this case, free units of polyions (which are not involved in interchain salt bonds) act as hydrophilic fragments, which retain IPEC particles in solution.

Water-soluble duplexes can be prepared also at Θ equal or close to unity, provided that $Z \neq 1$ or that the degree of polymerisation of an excess polyion, *viz.*, a host polyelectrolyte (HPE), is higher than the degree of polymerisation of another polyion present in a deficient amount, *viz.*, a guest polyelectrolyte (GPE). Then the solubility condition can be written as follows:

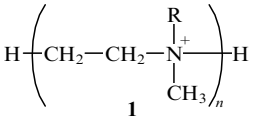
$$\varphi = \frac{[\mathrm{GPE}]}{[\mathrm{HPE}]} < \varphi_c < 1,$$

where φ is the ratio of the numbers of the charged GPE and HPE units in IPEC particles. In the case of a uniform distribution of GPE over HPE,

$$\varphi = Z.$$

The critical value φ_c is determined by the maximum population of HPE by GPE chains. At φ higher than φ_c, hydrophilicity of excess single-stranded regions of the chains is insufficient to retain all IPEC particles in solution. For most known systems, φ_c, which is determined primarily by the chemical structures of interacting polyelectrolytes, varies from 0.2 to 0.6.

In the pH region, enclosed by the potentiometric titration curves *1* and *2* (see Fig. 1), the cooperative character of multicentre electrostatic coupling provides high resistance of IPECs to dissociation into the individual starting components. The effective dissociation constant at Θ close to unity sharply decreases with increasing degree of polymerisation of GPE and approaches zero even for rather short oligomers. For example, in the case of polymer homologues of quaternised linear ethyleneimine (**1**) interacting with poly(methacrylate) (PMA) polyanions, the degree of dissociation of IPEC has become negligibly small already for octamers.[4,38] Analogous results were obtained in studies of the reactions of oligophosphates with poly(*N*-dimethylaminoethyl methacrylate) (PDMAEMA)[39] and the reactions of oligo-2,5-ionenes with polyacrylate (PA) polyanions.[40]



1 R = CH_3 or $CH_2C_6H_5$.

Consequently, IPECs produced in the absence of low-molecular-weight salts do not virtually dissociate into individual components once a particular critical length of polyions is achieved.

If one of the polyions can exist in solution in a specific ordered conformation (for example, like ionic polypeptides or DNA), an oppositely charged polyelectrolyte can either stabilise or destabilise this conformation upon complexation.[6,24] For example, the α-helical conformation of free poly-L-lysine (PL) is stable only in strongly alkaline media where this compound is uncharged. Upon protonation of amino groups in a mixed aqueous–ethanolic solution, this conformation of PL is transformed into an uncoiled conformation already at pH 9–8.5. It should be noted that even completely protonated PL in the PL–PMA duplex retains the α-helical conformation in a much broader pH range. The helix–coil transformation occurs only at pH 3.5–4.0, at which IPEC decomposes due to protonation of the COO^- groups of PMA.[6] In other words, complexation stabilises the α-helix of PL. The opposite situation is observed for poly-L-glutamic acid (PGA). The α-helical conformation of PGA is stable in acidic aqueous solutions and is transformed into a random-coil conformation as pH increases to 6.0–6.5. By contrast, the helix–coil transformation in the PGA–linear polyethyleneimine (PEI) system occurs already at pH 3.0–4.0, *i.e.*, in the pH region where the PGA–PEI polyelectrolyte complex is formed. Consequently, binding of the PEI polycation to the negatively charged α-helix is thermodynamically less favourable compared to binding to the negatively charged PGA random coil.[6] Another example refers to DNA. It is known that, in an aqueous solution, the double helix of native DNA exists in the B form. Upon the formation of native DNA duplexes with polycations, the B form is transformed into the more compact C or A form.[24]

1. Kinetics and mechanisms of polyelectrolyte coupling, exchange and substitution reactions

The course of a coupling reaction of two strong polyelectrolytes in salt-free media can be monitored by any method that allows one to measure the amounts of low-molecular-weight counterions released (elemental analysis, conductometry, ion-specific potentiometry, *etc.*). The limitations of the sensitivity of these methods arise when the interpolyelectrolyte reactions are performed in the presence of low-molecular-weight salts at concentrations substantially higher than the base-mole concentration of interacting polyelectrolytes.

If one polyelectrolyte is a weak polyacid or a weak polybase, the degree of conversion Θ can be determined by measuring pH.[6] However, this method is applicable only in a pH range where Θ is no higher than 0.4–0.5 (40%–50%).[24]

It is convenient to perform quantitative investigations of the formation and transformations of soluble IPECs by luminescence quenching. For this purpose, it is necessary to label one of the oppositely charged polyions with a chemically bonded luminescence group and to choose the second polyion such that it can interact with the former group and quench luminescence. The portion of labelled polyions interacting with quencher polyions can be calculated at any pH both in the presence and absence of low-molecular-weight salts by measuring the luminescence intensity and using the corresponding calibrations.

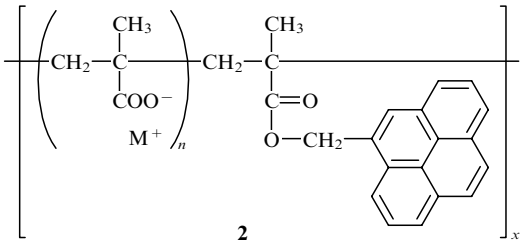
Luminescence quenching was used to study the kinetics of the coupling reactions of typical polyelectrolyte pairs. The conditions under which soluble IPECs dissociate into the starting components were determined. Direct experimental evidence for the ability of various soluble IPECs to be involved in competitive exchange and substitution reactions with other polyions was documented and the kinetics of these reactions was quantitatively studied.[41–44] It should be noted that the earlier study of the behaviour of DNA duplexes with poly(*N*-ethyl-4-vinylpyridinium) bromide in aqueous solutions[18] also provided indirect evidence for the possible polyion exchange.

Polyion exchange and substitution reactions can be represented in the general form as follows:

$$\underset{\text{(IPEC)}}{\mathrm{HPE_1}/n\,\mathrm{GPE}} + \mathrm{HPE_2} \rightleftharpoons \underset{\text{(IPEC)}}{\mathrm{HPE_1}/(n-x)\,\mathrm{GPE}} + \underset{\text{(IPEC)}}{\mathrm{HPE_2}/x\,\mathrm{GPE}}, \qquad (7)$$

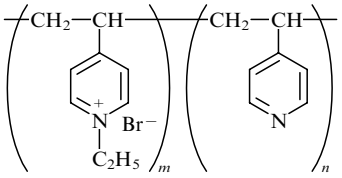
where n or x is the number of the GPE chains in IPEC particles. In terms of the above-mentioned approach, this process is a polyion exchange reaction if HPE_1 and HPE_2 are identical and a polyion substitution reaction if HPE_1 and HPE_2 differ in chemical structure. Different HPE segments can also exchange GPE polyions within one IPEC particle. This exchange is, in essence, equivalent to migration of GPE inside the HPE coil and serves as the mechanism of rearrangements within the complex giving rise to an equilibrium inner structure of IPEC particles and resulting in optimisation of their interactions with the environment.

In most kinetic studies,[41–48] fractions of polymethacrylic acid labelled with fluorescent anthryl or pyrenyl groups (PMA*)[49] (one label per 350–1500 repeated units) (**2**) served as a polyanionic component. The (*N*-ethyl-4-vinylpyridinium)–vinylpyridine copolymer (PVP) (**3**) was used as the polycationic component.



2

$n = 350–1500$.



3

This copolymer was prepared by quaternisation of poly-4-vinylpyridine fractions with bromoethane.[50] The number of quaternised units (*i.e.*, the linear positive-charge density) was specified by varying the degree of quaternisation (in %)

$$\beta = \frac{m}{m+n}100.$$

Most experiments described below (unless otherwise indicated) were carried out with the use of PVP whose degree of quaternisation was close to 100%. Quaternary vinylpyridinium units located in proximity to the anthryl and pyrenyl groups can quench fluorescence.

The kinetics of a typical coupling reaction of polyions was studied using the reaction of NaPMA* with PVP as an example.[45,47] The formation of the PMA*–PVP complex leads to a decrease in the fluorescence intensity of PMA* due to quenching of the pyrenyl labels with the quaternary vinylpyridinium units of PVP. The reaction mixture was prepared by the rapid addition of a calibrated aqueous PVP solution (0.02 ml) into a cell containing a calibrated aqueous NaPMA* solution (1.5 ml) with continuous stirring in such a way that the reagents were mixed for no longer than 2–4 s. The concentrations of the starting solutions were chosen so as to prepare a complex of the desired final composition. As can be seen from Fig. 2, mixing of the reagents in the absence of a salt is accompanied by a sharp decrease in the fluorescence intensity to a particular constant value. This corresponds to the rapid formation of contacts between PMA* and PVP (curve *1*). However, the decrease in the fluorescence intensity is smaller than that expected in the case of formation of the equilibrated PMA*–PVP interpolyelectrolyte complex of the desired composition (*cf.* curves *1* and *1′*). Moreover, mixing of the same reagents in the presence of NaCl (0.03 mol litre^{-1}) leads to a substantially larger initial decrease in the fluorescence intensity (*cf.* curves *2* and *2′* in Fig. 2).

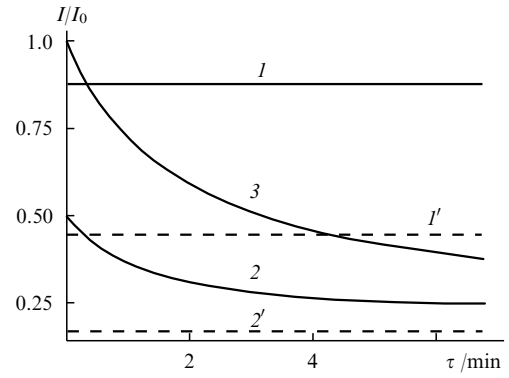


Figure 2. Typical kinetic curves of interpolyelectrolyte coupling and exchange reactions.[47]
I and I_0 are the current and starting fluorescence intensities, respectively, of PMA*; (*1*) NaPMA* ($P_w = 4.4\times10^3$, one label per 600 monomer units) + PVP ($P_w = 2.0\times10^2$, $\beta = 95\%$) in the absence of a salt, [NaPMA*] = 8.6×10^{-8} mol litre^{-1} (with respect to the polyion), Z = [PVP]/[NaPMA*] = 0.2; (*2*) the same reaction in the presence of sodium chloride (0.03 mol litre^{-1}); (*3*) IPEC (PMA–PVP) + NaPMA*, [NaPMA*] = [IPEC] = 8.6×10^{-8} mol litre^{-1}, $P_w = 4.4\times10^3$, $\varphi = 0.2$, $T = 20$ °C, pH 10, $\Theta \to 1$; (*1′*) the equilibrium limit for the curve *1*; (*2*)′ the equilibrium limit for the curves *2* and *3*; (*3*) the curve for pure polyion exchange.

Stop-flow measurements demonstrated that the fast step of polyion coupling reactions corresponding to an instantaneous drop observed in the kinetic curves is characterised by the rate constant of $\sim 10^9$ litre mol^{-1} s^{-1}. This value is close to the expected bimolecular rate constant of diffusion collisions of polyelectrolyte coils in a dilute solution.[45,47] Diffusion collisions of oppositely charged polyions lead to their association due to formation of random interchain salt bonds, *i.e.*, the formation of IPEC. However, at very low concentrations of simple salts or in their absence, rearrangements of randomly coupled polyions in exchange reactions are hindered. Hence, the resulting IPEC associates are 'frozen' in a non-equilibrium state (see curve *1* in Fig. 2). In the presence of a sufficiently large amount of a salt, the rate of polyion exchange, on the contrary, sharply increases. As a result, the initially non-equilibrated IPEC associates are rearranged with time and reach an equilibrium state, which is characterised by the maximum possible number of salt bonds between the interacting polyions. In other words, primary associates are transformed into equilibrated particles of the PMA*–PVP interpolyelectrolyte complexes (see curve *2* in Fig. 2). The pyrenyl labels attached to the PMA* chains give rise to additional hydrophobic interactions, due to which PMA*–PVP particles become more stabilised than PMA–PVP particles. As a consequence, the PMA* polyanions replace the PMA polyanions in the complex particles. Therefore, the kinetic curve *2* in Fig. 2 can be qualitatively considered as a superposition of the curves *1* and *3*. In other words, the presence of one pyrenyl group per several hundreds of monomer units in the PMA* chain appears to be sufficiently large for this chain to replace the chain of usual unmodified PMA initially bound to the PVP polycation.

For soluble IPECs, the polyion exchange reaction involving the transfer of one GPE (PVP) chain from HPE_1 (PMA) to HPE_2 (PMA*) in a dilute solution was demonstrated[46,47] to be characterised by second-order kinetics with respect to the concentrations of the polymers involved in the reaction (IPEC and PMA*).

$$\underset{\text{(IPEC)}}{\text{PMA/PVP} + \text{PMA*}} \rightleftharpoons \underset{\text{(IPEC)}}{\text{PMA*/PVP} + \text{PMA}}. \qquad (8)$$

The experimental kinetic curves fit well to straight lines in the coordinates of the equation

$$\frac{q}{1-q} = k_2[\text{PMA*}]_0 t, \qquad (9)$$

Table 1. Rate constants of the exchange reactions between the PMA–PVP interpolyelectrolyte complexes and NaPMA* at pH 10, $\Theta \to 1$, $T = 20$ °C.

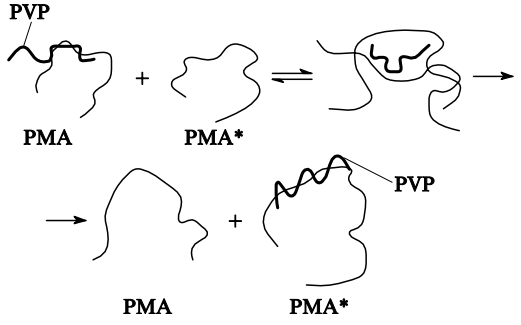
No	[NaPMA*] × 10^9 /mol litre^{-1}	$P_w \times 10^3$		β (%)	[NaCl] /mol litre^{-1}	$k_2 \times 10^5$ (see[a])
		PVP	PMA			
1	3	0.6	3.9	95	0.08	5.1
2	7	0.6	3.9	95	0.08	5.0
3	15	0.6	3.9	95	0.08	4.7
4	40	0.6	3.9	95	0.06	1.2
5	40	0.6	3.9	95	0.07	2.6
6	40	0.6	3.9	95	0.08	5.1
7	40	0.6	3.9	95	0.09	8.7
8	33	0.1	4.4	95	0.04	2.0
9	33	0.1	1.0	95	0.04	2.0
10	28	0.6	4.4	95	0.07	1.5
11	28	0.32	4.4	95	0.07	6.0
12	28	0.2	4.4	95	0.07	11.0
13	28	0.1	4.4	95	0.07	23.0
14	23	0.2	2.8	89	0.035	0.2
15	23	0.2	2.8	80	0.035	0.7
16	23	0.2	2.8	69	0.035	2.6
17	23	0.2	2.8	62	0.035	16.2
18	23	0.2	2.8	55	0.035	36.1

Note. P_w(PMA) = P_w(PMA*), PMA* contains one pyrenyl label per 350 units.

[a] In litre mol^{-1} s^{-1}.

where q is the degree of conversion in the reaction (8), and $[PMA^*]_0 = [PMA]_0 = [IPEC]_0$ are the starting molar concentrations of the reagents. The absolute rate constant (k_2) of the transfer of the GPE chain from one HPE chain to another under various conditions can be determined according to Eqn (9). As can be seen from Table 1, the constant k_2 is independent of the concentrations of the compounds involved in the reaction (runs 1–3 and 6), which is consistent with Eqn (9). It should be emphasised that the constant k_2 is also independent of the degree of polymerisation of HPE (PMA) (runs 8 and 9), but this constant decreases substantially with increasing degree of polymerisation of GPE (PVP) (runs 10–13). Under the experimental conditions, k_2 varied in a range of 10^4–10^6 litre mol^{-1} s^{-1}, *i.e.*, it is 3–5 orders of magnitude smaller than the estimated rate constant of diffusion collisions between the interacting particles. The results of investigations suggest that the transfer occurs in the intermediate ternary complex (PMA···PVP–PMA*) generated as a result of the mutual penetration of the chains of the starting IPEC and NaPMA* upon their random collisions in solution. This complex presented in Scheme 1 serves as a 'transition state' in the bimacromolecular polyion exchange reaction. Under the above-mentioned experimental conditions, only some collisions are productive. There are, on the average, 10^3–10^5 ineffective collisions per event of transfer of PVP from PMA to PMA*. The strong dependence of k_2 on both the salt concentration (runs 4–7) and the linear charge density of the PVP chains (runs 14–18) is in complete agreement with the proposed reaction mechanism.

Scheme 1



The polyion exchange processes with the involvement of IPEC particles containing more than one GPE chain are described by polychronic kinetics. However, factors governing these more complex reactions are qualitatively similar to the considered above simplest second-order reaction.[43] In particular, their rates also depend substantially on the concentrations of the additives of simple salts. This is confirmed by the following data:

$[NaCl] \times 10^3$ /mol litre^{-1}	0	35	70	100
Half-life /s	reaction does not occur	240	6	< 1.5

{P_w(NaPMA*) = P_w(NaPMA) = 3×10^3, P_w(PVP) = 2×10^2; [NaPMA*] = [NaPMA] = [IPEC] = 4×10^{-3} base-mol litre^{-1}, $\varphi = 0.33$; pH 10, $T = 20$ °C}.

The presence of salts substantially affects the polyion substitution reactions as well.[39, 40, 44, 48, 51–53] The replacement of the PMA* polyanions in the PMA*–PVP polyelectrolyte complex with the polyvinyl sulfate (PVS) polyanions is completely hindered in a salt-free solution but it is strongly accelerated in the presence of NaCl, as evidenced by the following results:

$[NaCl] \times 10^3$ /mol litre^{-1}	0	2	4	6	8	10
Half-life /s	reaction does not occur	600	60	13	5	< 1.5

{P_w(NaPMA*) = 3×10^3, P_w(PVS) = 1.3×10^3, P_w(PVP) = 2×10^2; [IPEC(PMA*–PVP)] = 4×10^{-3} base-mol litre^{-1}, φ = 0.2; [PVS] = [PVP]; pH 10, $T = 20$ °C}.

In substitution reactions, not only the kinetics but also the position of equilibrium depend substantially on the chemical nature of polyions. In particular, polyanions containing the sulfonate or sulfate group in the repeated monomer unit (PVS, polyethylene sulfonate, heparin, *etc.*) generally replace polycarboxylates (for example, PA or PMA) in polyelectrolyte complexes containing ammonium as the polycation.[40] The driving force for the substitution is a specific (in addition to Coulombic) affinity of the sulfonate or sulfate group for protonated or quaternary amino groups.

The dramatic influence of the degree of polymerisation of competitive polyelectrolytes and the chemical nature of a low-molecular-weight salt on the equilibrium degree of conversion was observed in the polyion substitution reaction of the PMA* (HPE)–PVP (GPE) interpolyelectrolyte complexes with polyphosphates (PP) with different degrees of polymerisation[48]

$$\underset{\text{(IPEC)}}{PMA^*/n\,PVP} + x\,PP \rightleftharpoons \underset{\text{(IPEC)}}{x\,PP/n\,PVP} + PMA^* \qquad (10)$$

A change in the equilibrium degree of conversion q_e in the forward reaction (10) with increasing concentration of the additives of simple salts is illustrated by Fig. 3. It can be seen that, all other factors being the same, the curve shape depends substantially on the degree of polymerisation of PP (Fig. 3 *a*) and the nature of the cation of the salt present as an additive (Fig. 3 *b*). At high salt concentrations, these differences are associated with the sign change. For PPs possessing the longest chain (230 monomer units), the equilibrium (10) in a 0.3 M aqueous NaCl solution at fixed base-mole concentrations of all polymers completely shifts to the right, whereas this equilibrium for short-chain PPs (20 monomer units) completely shifts to the left. For PPs with intermediate degrees of polymerisation, q_e has intermediate values. For PPs with a fixed chain length (70 monomer units), the equilibrium (10) in a 0.3 M LiCl solution completely shifts to the right, whereas this equilibrium in a 0.3 M KCl solution completely shifts to the left. Analogous phenomena were not observed in non-polymer systems. Moreover, this phenomenon can, apparently, be considered as a model of biologically important rearrangements, which occur in cells with the involvement of oppositely charged natural polyelectrolytes. Under the reaction conditions, inter-

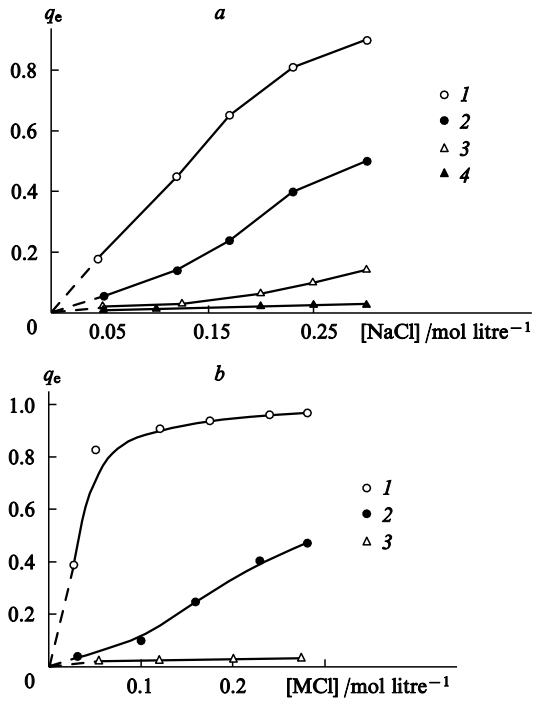


Figure 3. Plots of the equilibrium degree of conversion in the interpolyelectrolyte substitution reaction between IPEC (PMA*–PVP) and PP *vs.* the concentrations of NaCl (*a*) and other alkali metal chlorides (*b*).[48] [PMA*] = [PP] = 1.5×10^{-3} mol litre^{-1} (with respect to the monomer unit of the polyion), φ = [PVP]/[PMA*] = 0.33, T = 25 °C, pH 10; (*a*) the degree of polymerisation of PP is 230 (*1*), 70 (*2*), 50 (*3*), 20 (*4*); (*b*) the degree of polymerisation of PP is 70; (*1*) LiCl, (*2*) NaCl, (*3*) KCl.

polyelectrolyte complexes involved in the process (10) do not dissociate into the starting components and, consequently, the total number of free charged groups in unblocked regions of the competitive PMA* and PP polyanions remains unchanged. From this it follows that the sensitivity of the equilibrium (10) to the concentrations of external salts is determined by the difference in the concentration dependences of the effective binding constants of low-molecular-weight cations to the PMA and PP polyanions.

The qualitative thermodynamic explanation of these, at first glance, surprising effects was proposed in the study.[48] The main idea is as follows: the total change in the free energy for the reaction (10) can be represented as the sum of two terms

$$\Delta G_t = \Delta G_p + \Delta G_{ci}, \qquad (11)$$

where G_p is the change in the free energy due to the replacement of the salt bonds between PVP and PMA* with the salt bonds between PVP and PP, and G_{ci} corresponds to the difference in the free energies of interactions between low-molecular-weight cations and the PMA* and PP polyanions.

Let us consider the situation where the degrees of polymerisation of both polyanions (4100 for PMA* and 230 for PP) are higher than the degree of polymerisation of PVP (170). This is illustrated by Scheme 2. The total number of polymer particles in the system remains unchanged upon any shift of the equilibrium. As is evident from the foregoing, the equilibrium in NaCl solutions shifts to the right; that is the total change in the free energy G_t' in the case under consideration is negative, *i.e.*,

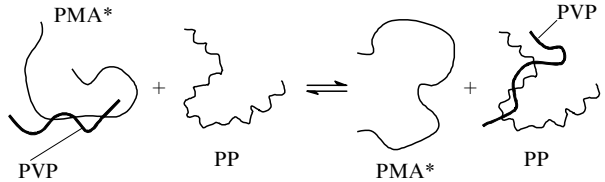
$$\Delta G_t' = \Delta G_p' + \Delta G_{ci}' < 0.$$

However, a decrease in the degree of polymerisation of PP leads to the shift of equilibrium to the left. Consequently, the free energy of the system should increase when moving from left to right, *i.e.*,

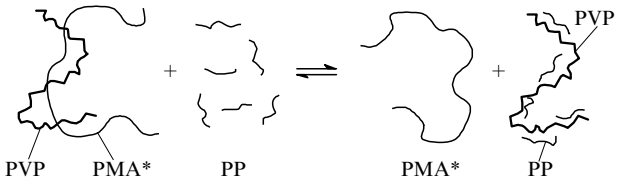
$$\Delta G_t'' = \Delta G_p'' + \Delta G_{ci}'' > 0.$$

This situation is illustrated by Scheme 3. Since the total number of the salt bonds between the oppositely charged polyions do remain constant (under the experimental conditions, Θ is close to unity for both IPECs), ΔG_{ci} is independent of the degree of polymerisation of the polyelectrolytes, *i.e.*, $\Delta G_{ci}' = \Delta G_{ci}''$. Consequently, the observed inversion of the equilibrium is associated with the increase in ΔG_p, *i.e.*, $\Delta G_p'' > \Delta G_p'$. Evidently, in contrast to the equilibrium presented in Scheme 2, the shift of the equilibrium in Scheme 3 from left to right, would lead to a decrease in the number of polymer particles in the system, *i.e.*, to a thermodynamically unfavourable decrease in the entropy of the system.

Scheme 2



Scheme 3



If the degree of polymerisation of PP is fixed, variations in the nature of the cation of a simple salt does not cause changes in the value of ΔG_p. Consequently, the change in the sign of ΔG_t in going from Li^+ to K^+ is associated with the change in ΔG_{ci}, *i.e.*, with the difference in the free energies of interactions between polyanions and simple cations. Evidently, this difference can be attributable only to the contribution of specific interactions superimposed occurring in addition to Coulombic attractions between opposite charges. Actually, the critical salt concentration at which the PMA–PVP polyelectrolyte complex dissociates into the individual polyelectrolytes (see below) increases in the series LiCl < NaCl < KCl, whereas the reverse order is observed for the PP–PVP complex.

An analogous influence of the nature of simple cations was observed in the presence of the competitive DNA and PMA polyanions.[51–53] The substitution reactions involving IPECs composed of DNA or PMA* and PVP were studied.

$$\underset{\text{(IPEC)}}{\text{PVP–PMA*}} + \text{DNA} \rightleftharpoons \underset{\text{(IPEC)}}{\text{PVP–DNA}} + \text{PMA*}. \qquad (12)$$

This reaction is completely reversible and reaches equilibrium regardless of the order in which the starting reagents are mixed. However, the reaction rate and the position of equilibrium depend substantially on the concentration and nature of the low-molecular-weight salt. For example, the change in the NaCl concentration from 0.125 to 0.25 mol litre^{-1} almost completely shifts the equilibrium to the right [from PVP–PMA* to PVP–DNA (Fig. 4*a*)]. In this case, the half-life decreases from tens of minutes to a few seconds. The dependences presented in Fig. 4*b* demonstrate the influence of the concentration and the nature of positive counterions on q_e. The shift of equilibrium to the left (from PVP–DNA to PVP–PMA*) increases in the series $Na^+ > K^+ > Li^+$. It should be noted that, in contrast to Na^+ and K^+, the effect of Li^+ depends on whether native or denatured

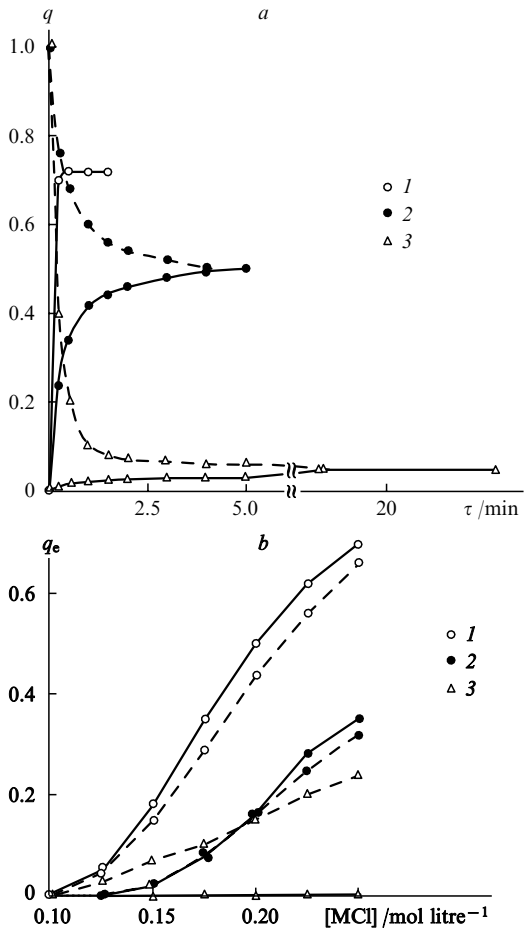


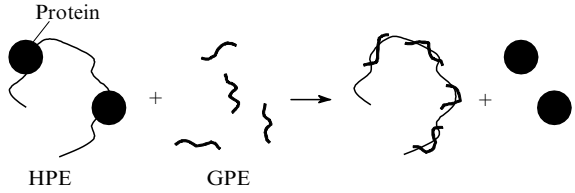
Figure 4. Kinetics of the interpolyelectrolyte substitution reaction (12) at different concentrations of NaCl (*a*) and the influence of the salt on the position of equilibrium of this reaction with native and denaturated DNA (*b*);[31]
(*a*) [NaCl] = 0.25 (*1*), 0.20 (*2*) and 0.125 mol litre^{-1} (*3*);
(*b*) sodium salt (*1*), potassium salt (*2*), lithium salt (*3*); solid lines refer to native DNA and dashed lines correspond to denaturated DNA.

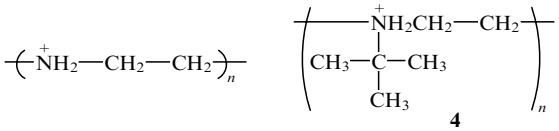
DNA is involved in the reaction (12). Actually, in the case of native DNA, unlike denatured DNA, the equilibrium completely shifts to the PVP–PMA* interpolyelectrolyte complex throughout the LiCl concentration range under study. Apparently, this difference is attributable to the fact that Li^+ cations have a higher affinity for native DNA than for denatured DNA. This fact is yet another example of the influence of specific interactions superimposed on usual Coulombic attractions.

Not only linear but also dendritic polyelectrolytes (dendrimers),[22–24] globular proteins[28,29] and other charged compact particles, for example, sols of polysilicic acid,[54–60] can serve as GPEs in the formation of IPECs. These IPECs remain in solution provided that the diameter of globules is much smaller than the contour length of linear HPE, and the population of HPE (the charge ratio) is no higher than a particular critical value. The mechanism of their formation is analogous to the above-considered mechanism of linear polyion coupling, and the equilibrium can be reached through rearrangements analogous to the above-described polyion exchange reactions. It should be noted that linear polyions with a rather high charge density on the chain generally replace globular particles, for example, proteins, in the starting IPEC (Scheme 4).[29]

Polyion exchange reactions, which play a decisive role in the establishment of equilibrium in IPEC-containing systems, can be hindered or completely frozen even in the presence of low-molecular-weight salts, if Coulombic interactions between polyions are enhanced due to other types of interactions, such as hydrophobic interactions, donor–acceptor bonds, *etc*. A typical example is the different solution behaviour of two similar non-stoichiometric IPECs containing identical polyanionic components, *viz*., NaPA or NaPMA, as HPE but different GPEs, *viz*., either linear PEI polycations or poly(*tert*-butyl aziridine) (PTBA) polycations. The latter has a linear charge density identical to that of protonated PEI (see structure **4**). Both interpolyelectrolyte complexes can exchange GPE at room temperature. However, at high temperatures (40–60 °C), at which hydrophobic interactions play a larger role, the PTBA chains, unlike the PEI chains, are fixed within the complex and do not migrate from one particle to another.[61]

Scheme 4





4

Other examples of the critical phenomena typical of polyion exchange reactions are considered below.

2. Properties of equilibrated non-stoichiometric interpolyelectrolyte complexes in solution

Nonstoichiometric IPECs can be considered as block copolymers containing free hydrophilic segments of HPE chains and relatively hydrophobic GPE–HPE domains.[3,5] In dilute solution, the behaviour of such equilibrated water-soluble IPECs (see above) is to some extent similar to the behaviour of usual polyelectrolytes. Methods for the preparation of soluble equilibrated non-stoichiometric IPECs composed of various GPE–HPE pairs were documented.[62–64] These methods have been also reviewed in detail in the publication.[3]

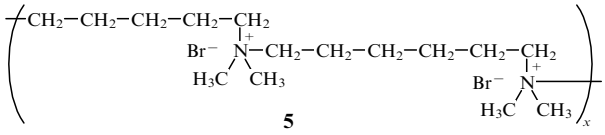
Studies by analytical ultracentrifugation,[54,62,63] gel-permeation chromatography[65] and light scattering[3,5,29,64,66] demonstrated that equilibrated water-soluble non-stoichiometric IPECs, which were prepared in dilute solutions from rather narrow molecular-weight fractions of HPEs and GPEs, occur as individual polymer particles. They are characterised by high compositional homogeneity and a narrow molecular-mass distribution. The characteristics of the PDMAEMA–PP polyelectrolyte complexes, which were prepared according to different procedures, are given in Table 2. Figure 5 *a* shows the Zimm plot for a solution of the thermodynamically equilibrated PDMAEMA–PP complex studied by quasi-elastic light scattering. This plot is similar to typical plots constructed by processing the light scattering data for solutions of usual polymers. Analysis of the characteristics given in Table 2 demonstrated that the procedure for the preparation of complexes has virtually no effect on the measured molecular mass (M_w), the radius of gyration (R_g), the second virial coefficient (A_2) and the sedimentation coefficient (S_c). However, the above-mentioned characteristics (except for M_w compensated due to release of counterions) are sensitive to the composition of IPEC. The characteristics of equilibrated non-stoichiometric IPECs in dilute aqueous salt solutions are given in Table 3. It can be seen that R_g and A_2 decrease, whereas S_c increases as the GPE/HPE ratio increases, *i.e*., as the effective charge of HPE decreases in the range of $0 < \varphi < \varphi_c$. At $\varphi < \varphi_c$, IPECs listed in Table 3 exist in dilute solutions as individual particles: each particle includes one HPE polyion containing a particular number of GPE molecules.

Table 2. Characteristics of interpolyelectrolyte complexes prepared by titration methods {HPE = PDMAEMA ($M_w = 6.3 \times 10^5$), GPE = PP ($M_w = 6.6 \times 10^4$), $\varphi = 0.33$, [NaCl] = 0.1 mol litre^{-1}, pH 4.0}.

Method of preparation of IPEC	$M_w \times 10^{-5}$	$(R_g^2)^{1/2}$ /nm	$A_2 \times 10^4$
Titration of HPE with a GPE solution	7.7	38	3.3
Titration of GPE with an HPE solution	7.7	39	2.9
Titration of a HPE–GPE mixture with hydrochloric acid	7.2	37	2.8

However, the situation changes substantially as φ_c is approached. This is manifested primarily in a substantial change in the Zimm plot, which becomes similar to the plots characteristic of polymers in poor solvents. The molecular mass of soluble particles increases. This is indicative of the formation of IPEC aggregates, which do not dissociate upon dilution. Simultaneously, the absolute value of the second virial coefficient A_2 sharply decreases and its sign changes from positive to negative (Fig. 5 *b*, Table 3, run 8).

In dilute solutions, the tendency of non-stoichiometric IPEC particles to aggregation depends on the chemical nature of HPE and GPE. In particular, this tendency increases with increasing hydrophobicity of the starting polyelectrolytes. As an example let us consider the behaviour of IPEC formed by NaPA (HPE) and



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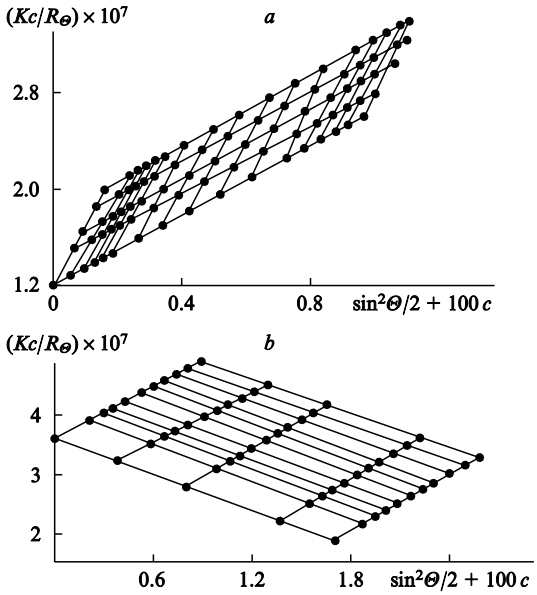


Figure 5. Zimm plots for a solution of the PDMAEMA–PP interpolyelectrolyte complex at $\varphi = 0.33$ (*a*) and 0.56 (*b*) (see runs 6 and 8, respectively, in Table 3) .
K is the optical constant, c is the concentration, R_Θ is the scattering intensity at the Θ angle.

5,6-ionene bromide (IB) serving as GPE.[67] Each repeated unit of the IB polycation (**5**) contains 5.5 methylene groups and two methyl groups per charge.

Table 3. Characteristics of equilibrated non-stoichiometric interpolyelectrolyte complexes in dilute aqueous salt solutions (20 °C).[3, 5, 58]

No	φ	Molecular mass of IPEC		n_{GPE} (see [a])	$(R_g^2)^{1/2}$ /nm	$A_2 \times 10^4$	S_c /Sv	Other conditions
		$M_w \cdot 10^{-5}$	$M_c \cdot 10^{-5}$					
Host polyelectrolyte — PDMAEMA; guest polyelectrolyte — NaPP ($M_w = 1.7 \times 10^5$)								
1	0	6.3	–	–	51	8.2	2.5	pH 4.0,
2	0.07	7.15	6.4	1.4	48	6.5	2.7	[NaCl] = 0.1 mol litre^{-1}
3	0.10	6.9	6.4	2.0	44	5.9	2.8	
4	0.13	7.35	6.5	2.3	43	5.2	–	
5	0.20	6.75	6.6	3.9	40	4.9	3.7	
6	0.33	6.7	6.8	6.5	35	2.9	6.0	
7	0.50	7.0	7.0	10.0	27	1.1	5.9	
8	0.56	28.0	–	–	27	−0.45	–	
Host polyelectrolyte — PDMAEMA, guest polyelectrolyte — NaPA ($M_w = 1.4 \times 10^4$)								
9	0	5.3	–	–	48.5	9.4	2.0	pH 4.5,
10	0.125	5.5	5.4	2.1	47.5	9.5	2.1	[NaCl] = 0.1 mol litre^{-1}
11	0.20	6.0	5.5	3.4	46.0	9.0	2.3	
12	0.33	5.6	5.6	5.6	43.5	8.6	2.6	
13	0.50	5.6	5.8	8.5	40.0	7.6	3.3	
Host polyelectrolyte — NaPP, guest polyelectrolyte — 5,6-ionene bromide ($M_w = 1.4 \times 10^4$)								
14	0	0.66	–	–	–	14.3	2.2	pH 7.0,
15	0.125	0.61	0.73	1.2	–	4.8	2.5	[NaCl] = 0.025 mol litre^{-1}
16	0.20	0.62	0.78	1.9	–	2.2	2.7	
17	0.33	0.66	0.85	3.1	–	1.7	3.4	

Note. The scattering intensities and refractive index increments were measured by varying the IPEC concentration at a constant concentration of a simple salt using dialysis of solutions of the samples against a solution of a common salt.[64] The molecular mass of IPEC of a given composition was calculated as follows: $M_c = P_{HPE}[m_{HPE} + \varphi(m_{GPE} - m)]$, where P_{HPE} is the degree of polymerisation of HPE, m_{HPE} and m_{GPE} are the molecular masses of the repeated units of HPE and GPE, respectively, m is the molecular mass of the salt eliminated upon coupling of polyelectrolytes; S_c was determined at a constant IPEC concentration of 0.35 mass %. [a] For all complexes, $n_{HPE} = 1$.

Table 4. Characteristics of IPEC formed from NaPA (HPE) and 5,6-ionene bromide (GPE) ($M_{w\,HPE} = 1.2 \times 10^5$, $M_{w\,GPE} = 1.4 \times 10^4$, pH 7.2, [NaBr] = 0.025 mol litre^{-1}, 20 °C).

No	φ	$M_w \times 10^{-5}$	n		$A_2 \times 10^3$
			HPE	GPE	
1	0.07	1.8	1	1.4	11.8
2	0.10	1.8	1	1.8	10.3
3	0.13	1.8	1	2.4	7.4
4	0.20	2.6	2	7.3	3.8
5	0.33	3.8	3	18.0	1.9

These groups are not sufficiently hydrophobic to suppress the solubility of the starting IB in water. However, in the presence of these groups, the affinity of IB–PA binary domains of IPEC for each other, apparently, increases. As can be seen from Table 4, the IB–PA particles undergo aggregation at $\varphi \geqslant 0.2$ (these values are, however, substantially smaller than φ_c) in contrast to IPECs listed in Table 3. Apparently, binary domains in aggregated IPECs form a water-insoluble core, while excess PA segments are exposed to water and form a crown, which imparts solubility to a particle as a whole.

Turning back to the experimental values of A_2, which decrease with increasing φ, recall that, according to the Donnan–Guggenheim theory,[68] the contribution of Coulombic repulsions between the charges of the polyion to the overall value of A_2 can be expressed as follows:

$$A_{2\,el} = \frac{1000 z_e^2 \gamma^2}{4M^2 I}, \qquad (13)$$

where z_e is the total charge of the polyion, γ is the degree of binding of the counterions to free HPE segments, M is the molecular mass of the polyion and I is the ionic strength equal to the concentration of a simple salt in solution. The effective charge of non-stoichiometric IPEC particles in the pH range corresponding to complete ionisation of HPE depends on φ

$$\frac{z_e}{M} = \frac{1-\varphi}{M_0}, \qquad (14)$$

where M_0 is the molecular mass of the repeated HPE unit. From Eqs (13) and (14) it follows that

$$A_{2\,el} \sim \frac{(1-\varphi)^2}{I}. \qquad (15)$$

Figure 6 *a* shows the dependence of the experimental values of A_2 on $(1-\varphi)^2$ at a constant ionic strength, which is in good agreement with relation (15). The latter is also applicable for the case where the ionic strength varies, whereas φ remains constant (Fig. 6 *b*). Assuming that the radius of gyration of an polyelectrolyte coil is directly proportional to the radius of the equivalent sphere and that the charge in the vicinity of the polyelectrolyte chain is primarily compensated by counterions and in accordance with the excluded volume theory, we can write

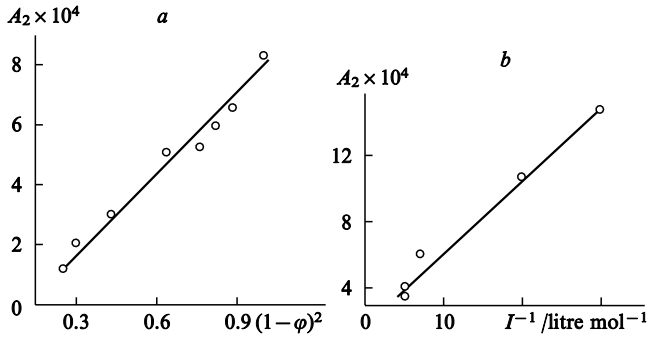


Figure 6. Dependences of the second virial coefficient (A_2) of solutions of IPECs prepared from PDMAEMA ($M_w = 6.3 \times 10^5$) and NaPP ($M_w = 1.7 \times 10^4$) on their compositions at a constant ionic strength I = [NaCl] = 0.1 mol litre^{-1} (*a*) and on the ionic strength at a constant composition (*b*);
(*b*): $\varphi = 0.33$; pH 4.0, $T = 20$ °C.

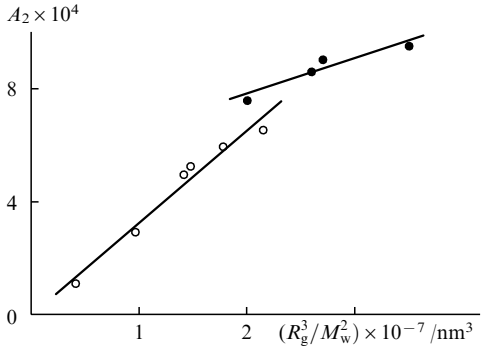


Figure 7. Second virial coefficients (A_2) in the coordinates of the equation (16) for different systems (see Table 3).

$$A_2 \sim \frac{R_g^3}{M_w^2}. \qquad (16)$$

The experimental data given in Table 3 agree well with relation (16) (Fig. 7).

The agreement between the experimental data and the above theoretical relations supports the conclusion that the behaviour of soluble equilibrated IPECs, whose compositions are in a range $0 < \varphi < \varphi_c$, in dilute solutions is analogous to that of usual polyelectrolytes with different charge densities.

The solution behaviour of non-stoichiometric IPECs formed upon complexation of linear HPE polyions with relatively small charged globular particles serving as GPE is similar to the behaviour of non-stoichiometric IPECs consisting of linear polyelectrolytes. In particular, this is true for cationic dendrimers,[22–24] proteins[28–30] and negatively charged sols of polysilicic acid,[55–60] which interact with linear polyelectrolytes with rather high degrees of polymerisation.

However, it should be emphasised that the above-described behaviour is untypical of IPECs formed by polyelectrolyte pairs, which are not prone to exchange reactions even if the starting components are taken in a non-stoichiometric ratio and an excess of polyions with a high degree of polymerisation is used. In such systems, the equilibrium is not established for kinetic reasons. Interpolyelectrolyte complexes formed by mixing polyamines or polyammonium salts with polysulfates or polysulfonates are examples of non-equilibrated systems. In such IPECs, interchain ion pairs are additionally stabilised by specific donor–acceptor interactions. In this case, complexation gives rise to relatively large IPEC aggregates containing a large amount of oppositely charged polyions. These aggregates are formed, in particular, in the reactions of sodium poly(styrene sulfonate) (NaPSS) with poly-*N*,*N*-dimethyl-*N*,*N*-diallylammonium chloride.[69–72]

3. Conversions of interpolyelectrolyte complexes in salt solutions

Typical plots of the reduced turbidity (τ/τ_{max}) *vs*. the ionic strength for HPE–GPE mixtures in water for $Z < \varphi_c$, Θ close to unity ($Z = \varphi$) and at a HPE concentration lower than the crossover concentration are presented in Fig. 8 *a*. The homogeneity region *I* corresponds to dilute solutions of equilibrated non-stoichiometric IPECs. These solutions are transparent, and IPEC particles in such solutions behave analogously to individual polyelectrolytes. It should be noted that the smaller φ, *i.e.*, the lower the population of HPE by GPE particles, the wider the region *I*. In region *II*, the system is also homogeneous. However, at these concentrations of

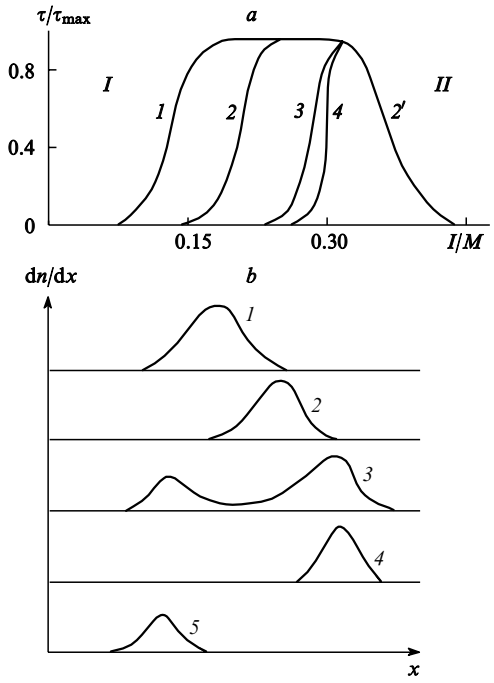


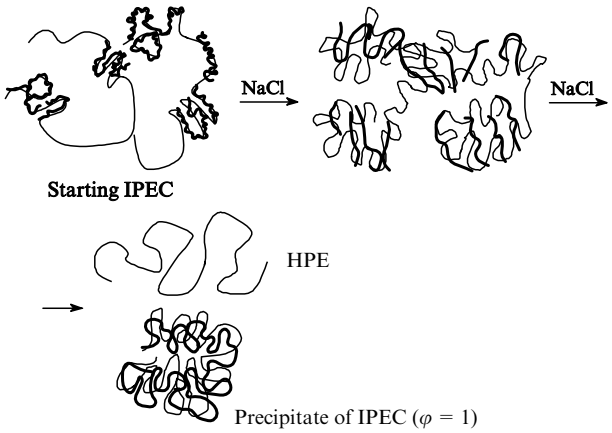
Figure 8. Phase behaviour of NaPMA ($M_w = 2.6 \times 10^5$)–PVP ($M_w = 6.0 \times 10^4$) mixtures depending on the ionic strength, which was varied by the addition of NaBr (pH 7.5, $T = 20$ °C);[71]
(*a*) plots of relative transmittance (τ/τ_{max}) *vs*. the ionic strength (I = [NaBr]) at $Z = 0.40$ (*1*), 0.33 (*2*, *2′*), 0.25 (*3*), 0.40 (*4*); (*b*) sedimentograms of the mixtures at $Z = 0.14$; (*c*) = 0.3 mass %, $\omega = 56\,100$ rpm, I = [NaBr] = 0.2 (*1*), 0.35 (*2*), 0.48 mol litre^{-1} (*3*); NaPMA (*4*) and PVP (*5*) at [NaBr] = 0.48 mol litre^{-1}.

low-molecular-weight salts, IPECs do not exist. In solution, they dissociate into the starting components because the oppositely charged polyions are shielded from each other by low-molecular-weight counterions. In the regions characterised by high turbidity, which are observed for different Z at intermediate salt concentrations, phase separation occurs and the systems become heterogeneous. The sedimentograms of the HPE–GPE system at different salt concentrations (profiles *1–3*) are compared in Fig. 8 *b* with the sedimentograms of individual HPE and GPE (profiles *4* and *5*). The profiles *1* and *2* are characterised by one sedimentation peak and belong to the homogeneity region *I*. The profile *3* has two peaks and corresponds to the heterogeneity region.[3, 73]

The phase behaviour of charge-non-stoichiometric mixtures of oppositely charged polyelectrolytes in salt solutions were studied in detail by light scattering methods, analytical and preparative ultracentrifugation, fluorimetry (in systems containing fluorescent-labelled HPE- and GPE-quenchers), phase composition analysis, *etc*.,[73–80] which provided deeper insight into the phenomenon as a whole.

An increase in the salt concentration within the homogeneity region *I* (see Fig. 8 *a*) deteriorates the thermodynamic quality of the solvent, which, in turn, leads to a decrease in the particle size of dissolved IPECs. The limiting concentration of HPE populated by GPE chains (at higher concentrations, phase separation occurs), which is determined by φ_c (I), also decreases. Hence, the higher the starting value of φ, $\varphi_0 = Z$, the lower the critical ionic strength (I_c), at which $\varphi_c(I)$ decreases to φ_0, and the broader the region *I* (see Fig. 8 *a*, curves *1–4*). To minimise the free energy of the system as a whole at $I > I_c$, the IPEC particles should loose a part of GPE chains. This occurs by redistribution of GPE chains between HPE chains according to the above-described mechanism of interpolyelectrolyte exchange. As a result, the reaction system undergoes disproportionation to give stoichiometric IPEC as an individual phase, while particles of non-stoichiometric IPEC of composition $\varphi' = \varphi_c(I) < Z$ (*i.e*., depleted in GPE compared to the starting particles) remain in solution. A further increase in the salt concentrations within the heterogeneity region leads to an increase in the amount of the stoichiometric complex, which forms an individual phase and remains in equilibrium with soluble IPEC particles of composition φ'. Evidently, under conditions where Θ is close to unity, φ' cannot be smaller than the ratio of the degrees of polymerisation of GPE and HPE. Then if $\varphi_c(I) < P_{GPE}/P_{HPE}$, free HPE chains remain in the supernatant after precipitation of stoichiometric IPEC (Scheme 5).[81] The maximum HPE concentration in the supernatant can be as high as $[HPE]_\infty = [HPE]_0(1-\varphi)$, where $[HPE]_0$ is its initial concentration.

Scheme 5



It should be noted that this phase behaviour of IPECs in salt solutions is not unambiguously determined by the ionic strength. The critical ionic strength I_c for each IPEC depends substantially on the nature of the HPE counterions.[73] The turbidimetric titration curves of the NaPA (HPE)–IB (GPE) polyelectrolyte complexes ($\varphi = 0.33$) with various simple salts are presented in Fig. 9. A comparison of the curves *1–4* shows that the critical ionic strength I_c decreases in the series $(CH_3)_4N^+$, K^+, Na^+, Li^+ as the affinity of the cation for the COO^- group increases.[81] At the same time, I_c is independent of the nature of the coanions of HPE, in particular, of F^-, Cl^- and Br^- (see Fig. 9, curves *2′–2‴*). The above data are consistent with the dependences of the sedimentation coefficients on the ionic strength of a solution for the PMA (HPE)–PVP (GPE) interpolyelectrolyte complexes ($\varphi = 0.37$) and free NaPMA at low concentrations of simple salts (*i.e* ., under conditions where IPECs are still quite stable).[77] It appeared that the addition of NaCl in the ionic

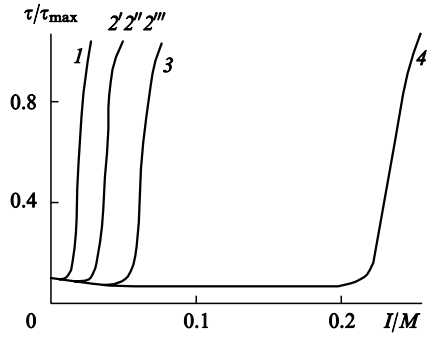


Figure 9. Plots of the relative transmittance (τ/τ_{max}) *vs*. the ionic strength for titration of IPEC formed in the NaPMA ($M_w = 1.8 \times 10^5$)–IB ($M_w = 1.4 \times 10^4$) mixture ($Z = \varphi = 0.33$) with solutions of LiCl (*1*); NaX, where X = F (*2′*), Cl (*2″*), Br (*2‴*); KCl (*3*); $(CH_3)_4NCl$ (*4*); the concentration of IPEC in the solution was 0.01 mass %, pH 8.5, $T = 20$ °C.[73]

strength range $0 < I < 0.1$ mol litre^{-1} leads to a substantial increase in S_c for both IPEC (from 1.7 to 4.35 Sv) and free NaPMA (from 1.3 to 2.5 Sv). This indicates that dissolved polymer particles become compact due to binding of the Na^+ counterions to negatively charged PMA units. The $(CH_3)_4N^+$ cations have a much lower affinity for carboxylate groups compared to the Na^+ cations. Hence, an equal increase in the ionic strength upon the addition of tetramethylammonium chloride to the system leads to only a slight change in the sedimentation coefficients S_c. Similar effects were observed also for soluble non-stoichiometric IPECs formed by cationic HPEs and anionic GPEs but in relation to the chemical nature of low-molecular-weight anions. For example, IPEC consisting of poly-*N*-ethyl-4-vinylpyridinium fluoride (HPE) and PMA (GPE) ($\varphi = 0.33$) decomposes at $[NaF]_c = 0.2$, $[NaCl]_c = 0.03$ and $[NaBr]_c = 0.01$ mol litre^{-1}. This order corresponds to an increase in the affinity of halides for the pyridinium units of HPE. In this case, I_c is completely independent of the nature of simple cations.[82]

The salt concentration at which IPEC dissociates into the starting polyelectrolytes, which pass into solution, and the phase-separated systems are again homogenised (*i.e.*, pass into region *II*, see Fig. 8 *a*) depends on the nature of both shielding counterions.[78, 79]

Figure 10 shows the plots of the relative fluorescence intensities of PMA* (HPE), which is initially involved into the soluble non-stoichiometric PMA* – PVP interpolyelectrolyte complex, *vs.* the concentrations of simple salts. The fluorescence intensity of the starting IPEC is low because of its quenching by the pyridinium rings of GPE. An increase in the fluorescence intensity in the course of titration of an IPEC solution with salts solutions is indicative of a decrease in the number of fluorescent labels in HPE, which interact with the GPE units. This may be a consequence of dissociation of interpolyelectrolyte duplexes. A sedimentation study of the NaPMA* – PVP electrolyte complexes in the corresponding salt solutions using a high-speed analytical ultracentrifuge equipped with a UV detector demonstrated that curves presented in Fig. 10 qualitatively describe the degree of cleavage of IPEC into the starting polyelectrolyte components.[80]

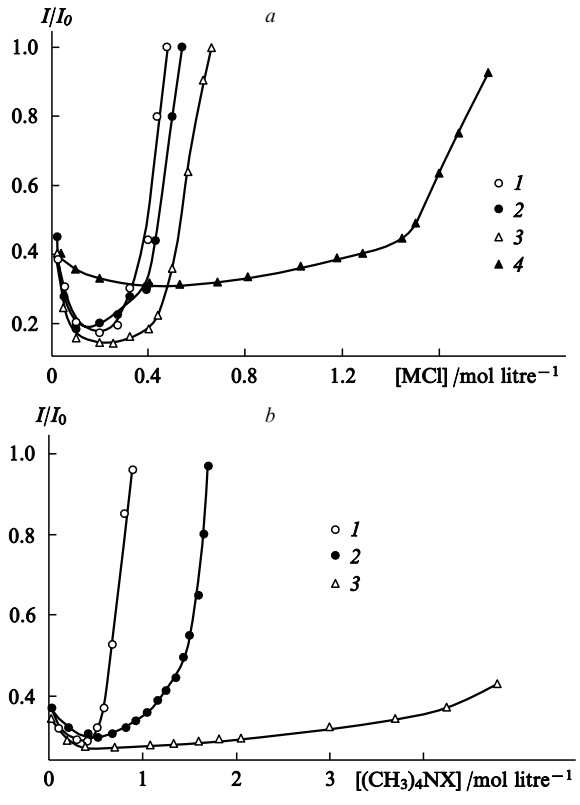


Figure 10. Plots of the relative fluorescence intensities (I/I_0) of a solution of IPEC formed from NaPMA* ($P_w = 2150$) and PVP ($P_w = 390$) *vs.* the concentrations of salts with various cations (*a*) and anions (*b*); $Z = \varphi = 0.3$, $[PMA^*] = 2 \times 10^3$ base-mol litre^{-1}, pH 9.5, $T = 20$ °C (I_0 is the fluorescence intensity of free HPE in an analogous solution of the salt).[77]
(*a*) M = Li (*1*), Na (*2*), K (*3*), $(CH_3)_4N$ (*4*); (*b*) X = Br (*1*), Cl (*2*), F (*3*).

A comparison of the fluorimetric titration curves of a PMA* (HPE) – PVP (GPE) solution with chlorides of various alkali metals and tetramethylammonium (Fig. 10 *a*) demonstrated that the ability of low-molecular-weight cations to shield interacting oppositely charged polyions (thus inducing dissociation of IPEC) decreases in the series $Li^+ > Na^+ > K^+ \gg (CH_3)_4N^+$. The affinity of the cations for polyanions of polycarboxylic acids decreases in the same order.[81] Figure 10 *b* displays the fluorimetric titration curves of the same IPEC with solutions of various tetramethylammonium halides. It can be seen that decomposition of IPEC can occur at a very low concentration of tetramethylammonium bromide (which determines the ionic strength of the solution), whereas the complex retains stability even at very high concentrations of tetramethylammonium fluoride. Tetramethylammonium chloride occupies an intermediate place. It should be noted that the affinity of halides for the PVP cations decreases in an analogous order.[82]

Analysis of the data presented in Fig. 10 *a* shows that the fluorescence intensity noticeably decreases at concentrations of alkali metal halides substantially lower than those necessary for decomposition of IPECs. Apparently, the formation of compact IPEC particles through specific binding of alkali metal ions to excess PMA units facilitates fluorescence quenching within IPEC particles. Such a decrease is not observed in the presence of tetramethylammonium salts due to a substantially lower affinity of the $(CH_3)_4N^+$ cations for COO^- groups.[79]

The threshold concentration of a low-molecular-weight salt necessary for decomposition of insoluble stoichiometric IPECs can be determined from a decrease in turbidity of the reaction mixture. This characteristic is independent of the degree of polymerisation of HPE, but it sharply increases (up to a certain limit) with increasing degree of polymerisation of GPE oligomers (Fig. 11).[80] However, it should be noted that a decrease in turbidity of the reaction mixture is not necessary indicative of the exhaustive cleavage of salt bonds and complete separation of the GPE and HPE chains, particularly, if GPE has a high molecular mass. Analysis of the results of sedimentation measurements demonstrated that a particular number of dynamic contacts between oppositely charged polyions can be retained even in a dilute solution, which appears in going through the clarification point. These contacts are completely broken only at higher salt concentrations.[78]

It should be emphasised that if the exchange of GPE between complex particles are, for one reason or other, forbidden, the

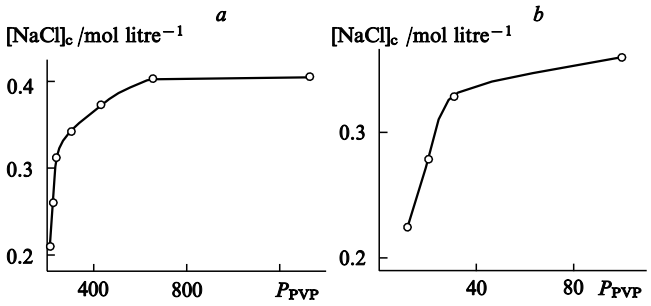


Figure 11. Change in the threshold concentration of sodium chloride necessary for dissociation of the PVP – PMA* interpolyelectrolyte complexes at high (*a*) and low (*b*) degrees of polymerisation of PVP.
$P_w(PMA^*) = 3.9 \times 10^3$, $\varphi = 0.30$, $T = 20$ °C.

addition of salts to solutions of non-stoichiometric IPECs does not lead to phase separation. In particular, the addition of NaCl to the above-mentioned solutions of the PA(or PMA)–PTBA polyelectrolyte complexes leads to phase separation at room temperature, but these solutions remain homogeneous at 40–60 °C because at these temperatures the polycation exchange is suppressed by hydrophobic interactions.[59] In PA (HPE)–PE (GPE) solutions, phase separation does not occur even at high salt concentrations if the HPE and GPE chains are linked not only through Coulombic interactions but also through a particular number of covalent bonds.[74–77] At a salt concentration sufficiently high for interpolyelectrolyte ion pairs to be broken, covalent bonds are retained. Hence, the IPEC particles behave here as graft copolymers present in a solution common to the main chain and grafted branches.

A new family of water-soluble IPECs referred to as block ionomer complexes (BIC) was documented.[83–86] These complexes include a block copolymer composed of a ionic and non-ionic water-soluble blocks. They can retain solubility even at $Z = \varphi = 1$, where Z is the charge ratio of the constituent polyelectrolytes. As an example we refer to the block ionomer complex formed by the diblock copolymer NaPMA ($P = 188$)–block-poly(ethylene oxide) ($P = 176$) and PVP ($P = 100$).[83] At $Z = \varphi = 1$, the BIC unimer contains a hydrophobic domain of the stoichiometric PMA–PVP interpolyelectrolyte complex covalently bonded to the hydrophilic poly(ethylene oxide) block, *i.e.*, it is virtually a complex amphiphilic macromolecule. The BIC unimers act as surfactants characterised by a particular critical micelle concentration. Actually, at concentrations higher than CMC, the unimers undergo aggregation to form polymer micelles, which contain an insoluble core assembled from IPEC domains and a crown consisting of poly(ethylene oxide) blocks. Due to the presence of the crown, micelles are soluble in water and are resistant to further aggregation. At the same time, BIC micelles can be involved in polyelectrolyte exchange reactions with homopolyelectrolytes (in particular, with NaPSS or NaPMA). Unlike all other polymer micelles, they undergo deaggregation upon the addition of low-molecular-weight salts. Deaggregation occurs due to destruction of the IPEC core caused by electrostatic shielding analogously to that described above for usual IPECs.[83]

Adsorption of polyelectrolytes on large oppositely charged surfaces can also be considered in terms of the IPEC formation. From this standpoint, adsorption of PVP on polystyrene latex particles coated with chemically bonded carboxyl groups was examined.[87–92] The diameter of latex particles (5×10^2 nm) was much larger than the contour line of the polyelectrolyte. The surface density of the carboxyl groups was ~ 5 nm^{-2}, and their $pK_a = 6.8$. At pH 9, at which all carboxyl groups are ionised, the starting electrophoretic mobility (EPM) of latex particles is negative. The dependence of EPM on Z is shown in Fig. 12. It can be seen that the surface charge decreases with increasing Z and becomes equal to zero at $Z = 1$. However in this case, in contrast to equilibrated stoichiometric IPECs formed in the reactions of completely ionised oppositely charged linear polyelectrolytes, a noticeable number of surface negative groups and positive units of the adsorbed polycations do not 'find each other' at the isoelectric point and, hence, cannot form contact ion pairs because of steric hindrance. The 'unpaired' units of the adsorbed polycations remain in loops and 'free tails'. These units, as well as 'unpaired' surface charges, are neutralised by low-molecular-weight counterions. Hence, the surface layer formed at the isoelectric point retains centres, which can adsorb both excess polycations (charge inversion) and polyanions, if they are added to the reaction system.

Actually, charge inversion of latex particles occurs at $Z > 1$, which indicates that excess polycations are adsorbed on these particles. At the same time, the dependence of EPM on Z is insensitive to changes in the latex concentration, which suggests that PVP is strongly bound to the adsorbent surface. Actually, titration of latex with a PVP solution affords the free polyelectrolyte, which is accumulated in solution only once it completely saturates the latex surface. In spite of this fact, the adsorbed polycations are easily exchanged between the latex particles through random collisions. This fact was established experimentally. The starting negatively charged latex (Fig. 12, arrow *a*) was mixed with an analogous latex, which was recharged with adsorbed PVP polycations (Fig. 12, arrow *b*). In the course of mixing, the latex particles bearing opposite charges undergo aggregation followed by spontaneous redispersion of these aggregates to individual particles whose size is identical to the particle size of the starting latex. However, EPM measured after redispersion has an intermediate value (Fig. 12, arrow *c*), which unambiguously indicates that mixing leads to redistribution of the adsorbed PVP polycations between the latex particles in the system.

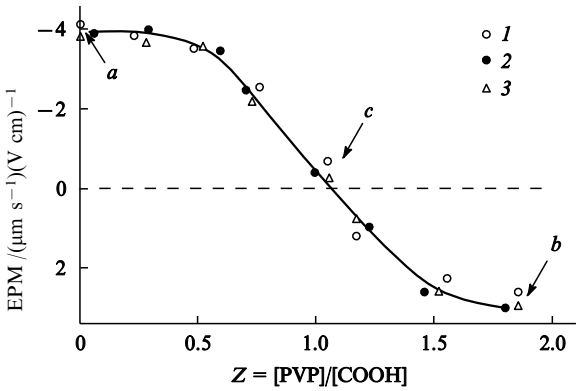


Figure 12. Dependence of the electrophoretic mobility of latex particles–PVP on the composition of their surface layer.
The concentration of the latex particles /litre^{-1}: (*1*) 1.8×10^{12}, (*2*) 1.8×10^{11}, (*3*) 9.0×10^{9}; pH 9.0, $T = 20$ °C.

$$\underset{\text{(IPEC)}}{\text{Latex}-\text{COO}^-/n\,\text{PVP}} + \text{latex}-\text{COO}^- \longrightarrow \underset{\text{(IPEC)}}{\text{latex}-\text{COO}^-/(n-x)\,\text{PVP}} + \underset{\text{(IPEC)}}{\text{latex}-\text{COO}^-/x\,\text{PVP}}. \quad (17)$$

Negatively charged small monolamellar liposomes (SML) display analogous behaviour in interactions with PVP.[92,93] Upon the addition of a PVP solution to a suspension of SML composed of the zwitterionic lipid, *viz.*, phosphatidyl choline (or dipalmitoyl phosphatidyl choline), and the anionic lipid, *viz.*, cardiolipin, the polycations are strongly adsorbed on the liposome surface. However, the subsequent addition of a NaPA solution leads to rapid removal of PVP from the surface due to formation of the even stronger PA–PVP interpolyelectrolyte complex. The SML–PVP complex, like usual IPECs, dissociates in the presence of low-molecular-weight salts (for example, NaCl). Both transformations are accompanied by complete regeneration of the starting SMLs.

The above examples reflect 'ideal relations' between polyelectrolytes and oppositely charged surfaces. This behaviour is typical only of systems, in which the electrostatic component plays the major role in adsorption. A different situation arises when other interactions (hydrogen bonds, hydrophobic or donor–acceptor interactions, *etc.*) are present in the system along with Coulombic attractions. In these systems, the polyion exchange or substitution does not occur, and the addition of low-molecular-weight salts does not cause desorption of polyions bound to the surface. For example, unlike PVP ($\beta > 90\%$), PVP copolymers containing hydrophobic regions are not desorbed from the surface of the above-mentioned SMLs upon the addition of NaCl.[93]

Presumably, nonideal electrostatic or strong non-electrostatic adsorption of a soluble polyelectrolyte on the solid sorbent surface plays the key role in the technology of the preparation of thin monolayer IPEC films.[7] In this case, adsorption gives rise to the

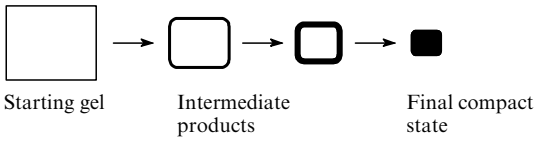
starting interface, which can strongly bind another oppositely charged polyelectrolyte as it comes in contact with its solution. This affords the first starting IPEC nanolayer. The latter serves as a basis for the formation and multiple reproduction of identical layers. These layers are deposited by successive immersion of the sorbent into solutions of oppositely charged polyelectrolytes. The factors suppressing polyelectrolyte exchange reactions are favourable for the retention of the continuity of each newly formed layer and regeneration of a 'sticky' interface necessary for each successive deposition.

III. Complexation of polyelectrolytes with oppositely charged hydrogels

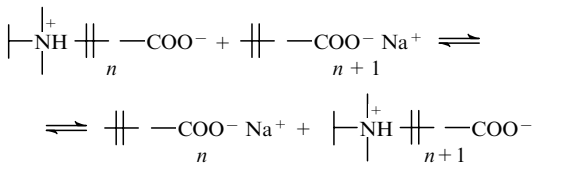
In the late 1980s, it was found that macroscopic samples of weakly cross-linked polyelectrolyte hydrogels (#PE) can adsorb oppositely charged linear polyelectrolytes from aqueous solutions to form cross-linked interpolyelectrolyte complexes (#IPEC).[94,95] Hydrogels containing 1–2 chemical cross-linkages per 200 repeated monomer units were investigated. In the initial state, their equilibrium degree of swelling was $\sim 10^3$. It appeared that complexation giving rise to #IPECs is controlled by the same factors as the reactions between oppositely charged linear polyelectrolytes. In the reactions involving weak polyelectrolytes as components, the pH range where #IPEC are formed and retain stability is bounded by the curves shown in Fig. 1.

Sorption of linear PEs was demonstrated to cause a sharp decrease in the volume of the hydrogel involved in the reaction (by 2–3 orders of magnitude). In the course of the interpolyelectrolyte reaction, a weakly swollen shell of the resulting #IPEC coexists with the strongly swollen core of the starting #PE. The coexisting regions are separated by a pronounced interface presented in Scheme 6.

Scheme 6

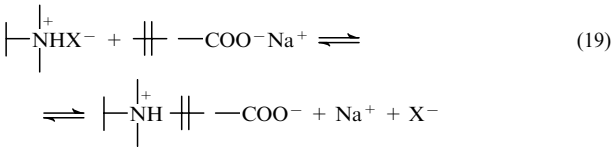


The sorption mechanism of soluble #PE involves two independent interpolyelectrolyte reactions. The adsorption-rate-determining step involves a 'relay-race' transfer of polyion segments from one fragment of the #PE network to another (initially vacant) through the interpolyelectrolyte exchange reaction



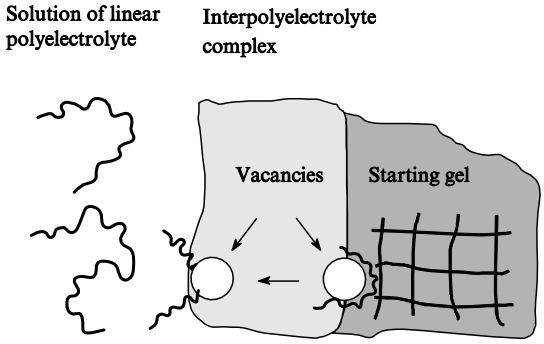
Each transfer event occurring at the shell/core interface and directed into the hydrogel phase affords a vacancy in the #IPEC shell, which becomes accessible for another segment of the polyion, thus allowing transfer in the same direction (Scheme 7).

As a result, the interface between the shell and the core moves to the centre of the sample involved in the reaction and the shell gradually extends over the whole starting #PE hydrogel. At the same time, charged vacancies together with their neutralising counterions move in the opposite direction and finally reach the interface between the #IPEC shell and the external solution, where they are bound to the oppositely charged polyions coming from the solution.



It is this coupling reaction that is the driving force for migration of polyions to the oppositely charged hydrogel. In other words, the free energy of the reaction (19) is consumed for the transport of polyions in the hydrogel phase, thus pushing the reaction (18).[94]

Scheme 7



Hence, the formation of #IPEC is thermodynamically controlled by the reaction (19), which occurs only under conditions (pH or the degree of ionisation of polyelectrolytes, α, the ionic strength) where the equilibrium shifts to the left. Correspondingly, #IPEC dissociates if the equilibrium (19) shifts to the left. In this case, linear polyions go back into the solution and the starting #PE hydrogel is completely regenerated. The composition of the final #IPEC is also determined by α .

The formation of #IPEC can be terminated in any intermediate step by ceasing the supply of polyions from the solution. If the conditions of stability of #IPEC are still met, the sharp interface between the shell and the core in the partially reacted sample (see Scheme 6) is not blurred and remains stationary for as long as desired. Hence, one can easily control the thickness of the #IPEC shell.

At the same time, the formation of #IPEC is kinetically controlled by the reaction (18).[95] The process is accelerated with increasing ionic strength (in the range of stability of IPEC) and with decreasing degree of polymerisation of the linear polyion. If the interpolyelectrolyte exchange reaction is forbidden for one reason or other, linear polyions do not penetrate into the #PE hydrogel. In this case, only a thin #IPEC film (its thickness is close to the diameter of the polyion) is formed on the hydrogel surface.[96] The data given in Table 5 describe the character of complexation of various #PE hydrogels with various linear polyelectrolytes. It can be seen that the factors suppressing the exchange reactions of soluble IPEC with linear polyelectrolytes (the presence of hydrophobic, sulfate or sulfonate groups in polymer chains) hinder the unlimited penetration of linear polyions into cross-linked hydrogels.

Cross-linked polyelectrolyte hydrogels can adsorb not only linear polyions but also oppositely charged globular proteins to form the corresponding #IPECs. This was exemplified for the first time by the reaction of strongly cross-linked sodium polyacrylate (#NaPA) hydrogel with lysozyme.[97] Later on, this phenomenon was studied in detail for sorption of cytochrome *c* and protamine by weakly cross-linked #NaPA hydrogels.[98,99] In particular, it was demonstrated that the number of salt bonds between the COO^- groups of #NaPA and the amino groups of the protein globule in salt-free systems is determined by pH, and the equilibrium composition of the final #IPEC formed in the presence of an excess protein in the reaction mixture is identical to the composition of IPEC precipitated by titration of a solution of linear NaPA with a solution of the corresponding protein. In the

Table 5. Character of complexation of cross-linked polyelectrolyte hydrogels with oppositely charged linear polyelectrolytes (20 °C).

Linear polyelectrolyte	M_w	Character of complexation
Hydrogel — #NaPA		
PVP	3×10^5	penetration inside
	1.5×10^5	the same
	0.5×10^5	"
PDMAEMA	6×10^4	"
PEI	6×10^4	"
Chitosan	2×10^5	"
PVPD [a]	1.7×10^3	surface adsorption
Hydrogel — #PDMAEMA		
NaPA	3.5×10^5	penetration inside
NaPMA	2.7×10^4	the same
	1.6×10^4	"
NaPSS	3.0×10^5	surface adsorption
NaPVS [b]	4.4×10^3	the same
Heparin	1.0×10^5	"

[a] The 70/30 *N*-ethyl-4-vinylpyridinium/*N*-dodecyl-4-vinylpyridinium copolymer. [b] Sodium poly(vinylsulfate).

intermediate steps of sorption of proteins by hydrogels from salt-free solutions, analogously to sorption of linear polyelectrolytes, the strongly swollen hydrogel core coexists with a well-defined compact shell of the resulting #IPEC, which is gradually thickened and finally takes up the whole starting hydrogel. However, the addition of low-molecular-weight salts to these systems, in contrast to the above-considered #PE/linear polyelectrolyte systems, not only affects the sorption kinetics but also radically changes the protein distribution within the partially reacted hydrogel, and the protein distribution changes from completely heterogeneous to virtually homogeneous.[99]

IV. Structures and mechanical properties of interpolyelectrolyte complexes in the bulk

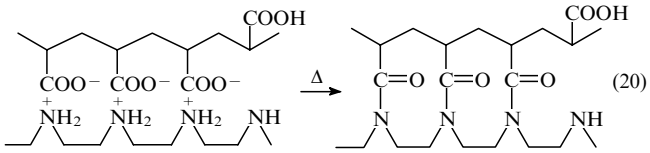
Although IPECs have been studied for many years, their structures and properties in the bulk remain poorly known. Unfortunately, scarce data were published primarily in sources that are difficult to access and, hence, are unknown to a wide range of researchers.

In early studies devoted to analysis of equilibria in coupling reactions of oppositely charged polyelectrolytes, IPECs were interpreted (on the basis of indirect evidence) as polymer compounds, in which polycations and polyanions are separated by more or less extended sequences composed of contact ion pairs coexisting with individual loops and tails. The latter can be considered as structural defects.[100] The higher the degree of conversion Θ, the larger the percentage of paired units in such IPECs (see Fig. 1). The percentage of free hydrophilic units in the loops and tails determines the maximum degree of swelling of IPEC in water. Swelling is limited by sequences of ion pairs, which, under the conditions of existence of IPEC, are stabilised by cooperative Coulombic interactions.

Unlike the equilibrated soluble non-stoichiometric IPECs considered above, insoluble stoichiometric IPECs, even those prepared in dilute aqueous solutions, undergo aggregation and form compact globular particles whose sizes are generally no smaller than tens of micrometers.[101–103]

The presence of structural defects in stoichiometric IPECs may be associated with 'freezing' of random interchain ion contacts, which appear in early steps of fast coupling reactions of polyions, resulting in the formation of IPEC particles as an individual phase. Then subsequent rearrangements of chains necessary for correction of defects proceed very slowly, particularly in the absence of low-molecular-weight salts. Slow relaxation of non-equilibrated IPECs prepared by neutralisation of strong polyacids with strong polybases was documented.[14, 103] However, if factors responsible for the formation of non-equilibrium structures are excluded, for example, in the preparation of stoichiometric IPECs by polymerisation of a ionic polymer on an oppositely charged polyelectrolyte matrix, the resulting products can be rather well ordered.[104–107]

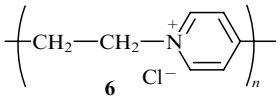
Generally, steric incompatibility between the interacting constituent polyelectrolytes is the main reason for the presence of structural defects in IPECs. The majority of known IPECs are coupling products of sterically irregular polyions. Such IPECs are X-ray amorphous. Studies by the ion-exchange equilibrium method demonstrated that at least 20%–30% of pairs of oppositely charged units in these IPECs are spatially separated.[108] In particular, even the product of the completed reaction of linear PEI with atactic PAA, whose chains are characterised by rather good steric compatibility, is X-ray amorphous. The IR spectroscopic study[109] demonstrated that at $Z = 1$, about 20% of the carboxy and imino groups in this IPEC are not involved in ion pairs but are located in structural defects. At the same time, domains of the PEI–PA interpolyelectrolyte complexes formed by contact ion pairs have, apparently, good short-range order. This is evidenced by the fact that heating of a dry PEI–PA film leads to the quantitative 'transformation' of the interpolyelectrolyte ion pairs into covalent amide bonds to form a ladder structure.



(20)

The carboxy and amino groups occupying defect sites are not involved in this reaction.[109–111]

However, the aforesaid does not mean that crystalline IPECs cannot be prepared by direct mixing of oppositely charged polyelectrolytes. In particular, IPECs, which were prepared by mixing solutions of ionene (**6**) and isotactic NaPA[107] or NaPP,[112, 113]



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are characterised by a very high degree of crystallinity. In any case, stereoregularity and particular steric compatibility between oppositely charged polyelectrolytes are, apparently, the necessary conditions for IPEC crystallisation.

Important data on the conformations of individual chains in solid IPEC consisting of high-molecular-weight PMAK and chitosan ($M_w = 1.9 \times 10^5$), $Z = 1$, were obtained by small-angle neutron scattering.[114] A mixture of usual PMAK [PMAK(H), $M_w = 3 \times 10^5$] and 2% deuterated PMAK [PMAK(D), $M_w = 1.1 \times 10^5$, $M_w/M_n = 1.25$] was used as the polyanion. Samples of IPEC as 0.1-mm-thick homogeneous films were prepared from solutions of polyelectrolytes in a common solvent, *viz*., an aqueous formic acid solution. Films formed after evaporation of the solvent were thoroughly washed with water and dried *in vacuo*, as was described in the study.[115] Samples of PMAK, which were used for measuring unperturbed sizes of the PMAK(D) chains, were prepared as thin films from an aqueous solution containing 2 mol.% PMAK(D) and 98 mol.% PMAK(H). In these experiments, PMAK(H) films were used as reference samples. Small-angle neutron scattering measurements were carried out in the scattering vector (Q) range $4 \times 10^{-5} \leqslant Q \leqslant 8 \times 10^{-4}$ nm^{-1}, where $Q = 4\pi(\sin\theta)/\lambda$, 2θ is the scan angle and $\lambda = 3.03 \times 10^{-2}$ nm is the average wavelength of the incident neutron beam. The spectral half-width was $\Delta\lambda/\lambda = 0.35$.

In the case of PMAK(D) strongly 'diluted' with PMAK(H), intramolecular interference from PMAK(D) may be ignored. Then, the Debye equation for coil-like chains

$$I(Q)^{-1} = I(0)^{-1}\left(1 + \frac{Q^2 R_g^3}{3}\right) \quad (21)$$

is fulfilled at $QR_g < 1$, where $I(Q)$ and $I(0)$ are the scattering intensities at $Q \neq 0$ and $\theta = 0$, respectively.

Since chitosan and PMAK(H) are characterised by virtually equal scattering densities, the radius of gyration of the PMAK(D) chain in IPEC was determined from Eqn (16). Figure 13 displays the plots of $I(Q)^{-1}$ *vs.* Q^2 for IPEC and PMAK samples at small scattering vectors Q. The observed equality of the extrapolated values of $I(Q)^{-1}$ suggests that the contrast PMAK(D) chains in both samples are uniformly distributed and are not aggregated. For PMAK(D) in the PMAK(H) matrix, $R_g = 10.2 \pm 0.3$ nm exactly corresponds to the expected unperturbed size. By contrast, $R_g = 17.5 \pm 0.5$ nm for PMAK(D) in the IPEC matrix, which is indicative of a noticeable elongation of the PMAK coils interacting with chitosan. However, the shape of these elongated coils deviates only slightly from the Gaussian. Processing of the neutron scattering data for PMAK(D) in the PMAK(H) matrix (Fig. 14, curves *1* and 2) at $QR > 5$ gives $I(Q) \sim Q^{-2}$, which is complete agreement with the Gaussian distribution. For PMAK(D) in the IPEC matrix, $I(Q) \sim Q^{-2.2}$.

Unfortunately, the above-described experiments are, to my knowledge, the only example of studies of the IPEC structure in the solid state by small-angle neutron scattering. Undoubtedly, further systematic investigations in this field will be highly informative and useful.

Air-dry amorphous IPECs in the bulk are transparent fragile materials. For most of them, water serves as a common plasticiser: IPEC films weakly swollen in water (tens of percentage at $Z = 1$) are flexible and elastic. Homogeneous IPEC films can be formed from solutions of the corresponding polyelectrolytes, if their premature electrostatic binding to each other in solution is prevented in one way or another. For a pair of strong polyelectrolytes, mixed aqueous-organic solvent containing a shielding low-molecular-weight salt (for example, NaCl or NaBr) and a volatile organic component (for example, acetone or dioxane) are used, which hinders salting-out of the polyelectrolytes from the solution. After evaporation of the mixed solvent, the films are repeatedly washed with water to remove inorganic salts.[1, 15, 116] In the case of weak polyelectrolytes, their premature binding in solution can be prevented by shifting pH for a time from the stability range of IPEC to an acidic or basic region (see Fig. 1). This is achieved by adding a volatile acid (for example, formic or acetic acid) or a volatile base (for example, ammonia or trimethylamine).[115]

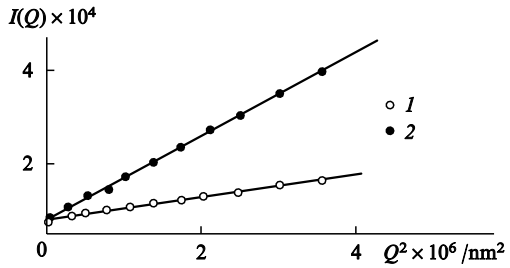


Figure 13. Initial regions of the small-angle neutron scattering curves for PMAK(D) in the PMAK(H) matrix (*1*) and for PMAK(D) in the matrix of the PMAK – chitosan interpolyelectrolyte complex (*2*).

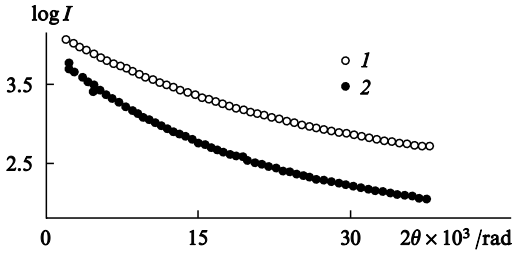
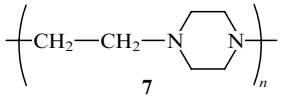


Figure 14. Full experimental small-angle neutron scattering curves for PMAK(D) in the PMAK(H) matrix (*1*) and for PMAK(D) in the matrix of the PMAK – chitosan interpolyelectrolyte complex (*2*).

The mechanical properties of IPECs formed by pairs of strong polyelectrolytes have not been studied systematically. However, it was noted that the most strong water-swelling IPEC films, which were tested as potential ion-exchange and separating membranes for salting-out of water, are formed at $Z = 1$, *i.e.*, when the maximum number of interpolyelectrolyte salt bonds per unit volume are present.[1]

A more complex situation occurs with IPEC membranes involving weak polyelectrolytes,[115] in particular, poly(ethylenepiperazine) (**7**) (PEP, $M_\eta = 3 \times 10^5$) and PAA ($M_\eta = 3 \times 10^5$).



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Their mechanical properties were studied in detail.[117] Films of different compositions $Z = [PAA]/[PEP]$ were prepared from 50% aqueous formic acid. Load – deformation curves describing the viscoelastic properties of equilibrium swollen films of PAA – PEP interpolyelectrolyte complexes of composition $Z \geqslant 1$ immersed in aqueous solutions are presented in Fig. 15*a*. The majority of water-swollen PECs are characterised by analogous

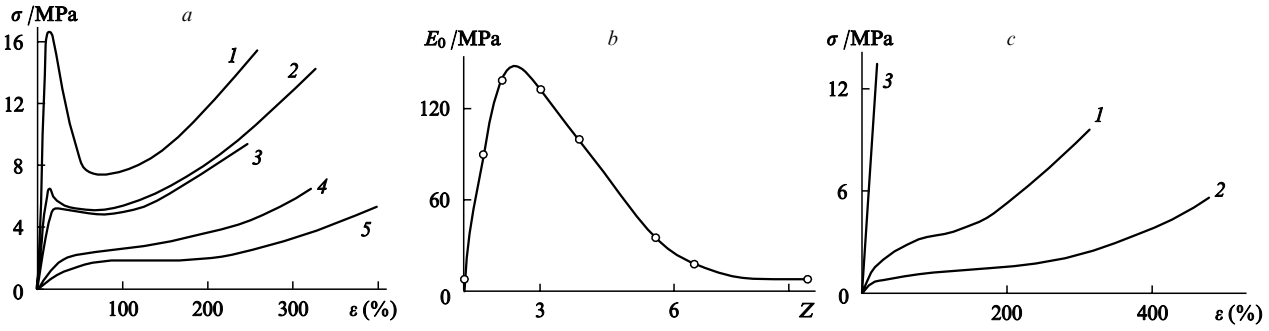


Figure 15. Viscoelastic properties of the PAA – PEP interpolyelectrolyte complexes;
(*a*) load – deformation curves for IPECs of various compositions in an aqueous solution, pH 6.0, $T = 20$ °C; $Z = [PAA]/[PEP] = 2$ (*1*), 1.5 (*2*), 5 (*3*), 7 (*4*), 1 (*5*); (*b*) the plot of the initial Young's modulus of IPEC *vs.* the composition; (*c*) load – deformation curves for IPEC ($Z = 1$) in water (*1*), an aqueous NaCl solution (5 mass %) (*2*) and dioxane (*3*).

load–deformation curves. However, in contrast to IPECs consisting of a pair of strong polyelectrolytes, the maximum rupture stress (Fig. 15 *a*) and Young's modulus (Fig. 15 *b*) are observed at $Z = 2$ rather than at $Z = 1$. In other words, PAA-rich films are most strong. The minimal equilibrium degree of swelling corresponds to the same composition (~35%). At $Z < 1$, the strength of the films is even smaller than that at $Z = 1$. Undoubtedly, the role of intermolecular salt bonds, which reinforce a film structure, in these materials is as important as in IPECs formed by strong polyelectrolytes. In particular, this is evident from a consideration of the load–deformation curves presented in Fig. 15 *c*. It can be seen that a sample, which was initially immersed in a solution of a low-molecular-weight salt responsible for shielding of salt bonds between the oppositely charged polyions and then tested in the same medium, is characterised by much smaller initial Young's modulus and yield stress. At the same time, the replacement of water with a water–dioxane mixture or pure dioxane leads to substantial strengthening of IPEC films due to an increase in stability of the ion pairs as a result of a decrease in the polarity of the medium. Nevertheless, analysis of the mechanical behaviour of PAA–PEP films containing excess PAA demonstrates that additional hydrogen bonds also contribute substantially to stabilisation of the IPEC structure. For example, the initial Young's moduli of films of PAA–PEP interpolyelectrolyte complexes decrease with increasing temperature (Fig. 16). For PAA-rich IPECs, the Young's moduli decrease more substantially and are characterised by more pronounced cooperativity.

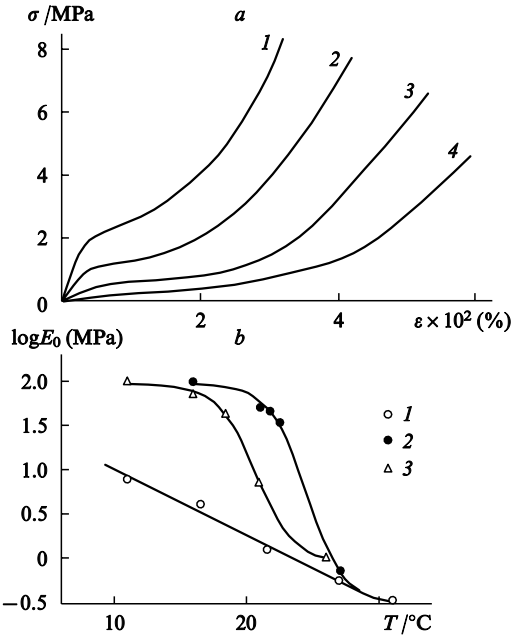


Figure 16. Temperature dependence of the viscoelastic properties of the PAA–PEP interpolyelectrolyte complexes in an aqueous solution, pH 6.0;
(*a*) load–deformation curves measured at 10 (*1*), 20 (*2*), 30 (*3*), 40 °C (*4*); (*b*) the temperature dependence of the initial Young's modulus, $Z = 1$ (*1*), 3 (*2*), 5 (*3*).

V. Conclusion

Vital functions of any complex biological construction were determined not only by precisely programmed molecular structures of the starting constituent biopolymers but also by the controlled mechanisms of their self-assembly and reorganisation. The structures of supramolecular biological particles are formed as a result of establishment of balance between superimposed multipoint interactions, some of them being oppositely directed (hydrogen, hydrophobic and donor–acceptor bonds, electrostatic attraction and repulsion). Hence, along with retention of extraordinary stability under particular conditions, biological structures can undergo rearrangements and substantial reorganisation even upon insignificant changes in the environmental medium. These characteristic features are, to some extent, typical also of IPECs constructed from synthetic polyelectrolytes. The phenomena, characteristic features and their interpretation presented in this review may be useful in controlling the synthesis, structure and properties of IPECs prepared for various technical and biomedical applications.

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