



UDC 537.226:544.163.2

*T.P. Stepanova*¹, *T.D. Anan'eva*¹,
*E.D. Karpenko*², *V.M. Kapralova*²

¹ Institute of Macromolecular Compounds RAS
31 Bolshoy Ave. V.O., St. Petersburg, 199004, Russia

² St. Petersburg State Polytechnical University,
29 Politekhnikeskaya St., St. Petersburg, 195251, Russia

**A DIPOLE MOMENT AND CONFORMATIONS
OF POLY-N-VINYLPYRROLIDONE AND OF ITS COMPLEX
WITH C₆₀ FULLERENE IN AQUEOUS SOLUTIONS**

*T.П. Степанова, Т.Д. Ананьева,
Е.Д. Карпенко, В.М. Капралова*

**ДИПОЛЬНЫЙ МОМЕНТ И КОНФОРМАЦИОННЫЕ СВОЙСТВА
ПОЛИВИНИЛПИРРОЛИДОНА И ЕГО КОМПЛЕКСА
С ФУЛЛЕРЕНОМ C₆₀ В РАСТВОРЕ В ВОДЕ**

The study of temperature dependences of dipole moments and conformational properties of poly-N-vinylpyrrolidone (PVP) and polymer complex of PVP with C₆₀ fullerene (PVP + FC₆₀) was carried out in dilute aqueous solutions at 293–313 K. It was shown that dipole moment values for PVP and PVP + FC₆₀ were 24–32 D and 18 D, correspondingly. The presence of the molecular group –N–C=O in each monomer unit near the macromolecule backbone promotes the formation of helical blocks in macromolecular coils. In external electric field, the non-alternating projections on the direction of this field and on the vectors connecting the neighboring segments of the macromolecule appear. It was demonstrated that the changes in the characteristics of the dielectric polarization could be explained by structuring in the coils of PVP and PVP + FC₆₀ in aqueous solutions.

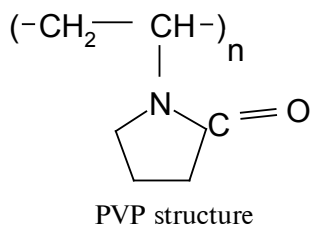
DIELECTRIC PERMITTIVITY, DIPOLE MOMENT, HELICAL BLOCKS IN COILS, ASSOCIATION, SOLUTION.

Проведено исследование дипольных моментов поли-N-винилпирролидона (ПВП) и на его основе полимерного комплекса с фуллереном C₆₀ (ПВП + C₆₀). Показано, что значения дипольного момента ПВП и ПВП + C₆₀ в водных растворах в условиях бесконечного разбавления велики и составляют 24 – 32 Д и 18 Д (T = 293 – 313 К) соответственно. Анализ экспериментальных результатов указывает на специфические конформационные свойства макромолекул исследованных полимеров. Наличие молекулярной группы –N – C = O в каждом мономерном звене у хребта макромолекулы обуславливает возникновение спирализованных блоков внутри макромолекулы. В этом случае во внешнем электрическом поле возникает неальтернирующая составляющая дипольного момента на направление спирали. Суммарный эффект векторного сложения этих дипольных моментов и взаимоориентация спирализованных блоков в статистическом клубке определяют высокие значения дипольных моментов ПВП и ПВП + C₆₀ в водных растворах.

ДИЭЛЕКТРИЧЕСКАЯ ПРОНИЦАЕМОСТЬ, ДИПОЛЬНЫЙ МОМЕНТ, СПИРАЛИЗОВАННЫЕ БЛОКИ, АССОЦИАЦИЯ, РАСТВОР.

Polyvinylpyrrolidone (PVP) is known to be one of amphiphilic polymers which are inclined to self-organization into various aggregates in

both polar and non-polar environment [1]. Stable aggregate formation in the solutions of amphiphilic polymers is due to hydrophobic



and ionic interactions resulting in H-bonds, charge transfer complexes, coordination complexes, etc. PVP ability to form complexes as well as its other physical, chemical and biological properties make this polymer suitable for technological and biomedical applications. PVP structural formula is given in scheme. The PVP solubility in water is mostly due to the lactam cycle.

Recently, the synthesis of PVP with biological or technogenic inclusions of macromolecular scale has been described, and the main attention was paid to PVP and fullerene C_{60} (FC_{60}) complexes using in medical applications. The use of fullerenes in medicine faces significant difficulties because of their almost total water insolubility, though it could be overcome by using fullerene non-covalent complexes with water soluble polymers like PVP. In this case, the electronic structure and therefore the properties of fullerene molecular clusters are disturbed minimally in contrast to covalent bonding. It is obvious that physical and chemical properties of non-covalent complexes are determined by the proportion of fullerenes and polymer in the complex [2]. It is well-known that fullerene molecule has a form of truncated icosahedron with the surface consisting of hexagons and pentagons connected by single and double bonds. The molecule FC_{60} diameter is shown to be approximately 10.2 Å [3].

The purpose of the present paper is to investigate and compare the dipole moments and conformational properties of PVP and PVP + FC_{60} complexes in aqueous solutions under the conditions of infinite dilution.

To produce the PVP + FC_{60} complex, PVP with molecular mass of 24000 produced by «Fluka» and C_{60} fullerene from the company «Fullerene technologies» (St.-Petersburg) with fullerene content of 99.5 % were used [4 – 7]. PVP used for this work is the white-

yellow powder with softening temperature as high as 160 °C, density $d_{20} = 1.9 \text{ g/cm}^3$ [1] and refraction index $n_{D20} = 1.58$ (for a film).

The solutions of PVP in chloroform (50 mg/ml) and of fullerene in *o*-dichlorobenzene (0.8 mg/ml) were mixed with the volume proportion 2 : 1, then the solvents were evaporated in vacuum at 35 – 40 °C, and the solid residual was dried. To remove free fullerenes, the solid residual was stirred into water and filtered through the filter paper. This procedure was followed by water vacuum evaporation at the same temperature.

Fullerene concentration in the complex was estimated by complex destruction in 2 mg/ml solution in the mixture of ethanol and toluene 1 : 9. Fullerene concentration in the mixture of solvents was measured by UV spectroscopy method [7] and brought into correlation with PVP concentration.

The capacity of solution was measured in the cell with platinum electrodes [9] using measuring the bridge E7-12 at the frequency of 1 MHz with the error of 0.001 pf. The capacity of the used cell was 4.53 pf.

The solutions of PVP and PVP + FC_{60} in distilled water for further measurements were prepared using gravimetric method.

Dipole moments of PVP molecules and PVP + FC_{60} complexes in aqueous solutions were estimated according to Buckingham theory of statistical polarization [8] for two-component systems:

$$\begin{aligned}
 & \frac{(\varepsilon_{12} - 1)(2\varepsilon_{12} + 1)}{3\varepsilon_{12}} V_{12} - \frac{(n_1^2 - 1)(2\varepsilon_{12} + 1)}{(2\varepsilon_{12} + n_1^2)} V_1 x_1 - \\
 & - \frac{(n_2^2 - 1)(2\varepsilon_{12} + 1)}{(2\varepsilon_{12} + n_2^2)} V_2 x_2 = \\
 & = \left(\frac{4\pi N_A}{3kT} \right) \mu_{1ef}^2 x_1 + \mu_{2ef}^2 x_2.
 \end{aligned} \tag{1}$$

Here ε is dielectric permittivity; n – refraction index; V – molar volume, $V = Mv_s$ (v_s – specific volume, M – molar mass); x – mole per cent, T – absolute temperature, N_A – Avogadro number, k – Boltzmann constant, μ_{ef} – effective dipole moment (indexes 1, 2 in 12 are for solvent, dissolved substance and solution, accordingly).

According to the statistical theory of dielectric polarization,

$$M_{ef}^2 = \mu^2 g, \quad (2)$$

where g is a correlation parameter for dipole moments orientation characterizing short-range interactions; μ – dipole moment of a polar molecule related to its dipole moment in vacuum μ_0 by

$$\mu = \frac{n^2 + 2}{3} \cdot \frac{2\varepsilon + 1}{2\varepsilon + n^2} \cdot \mu_0. \quad (3)$$

Dipole moments μ_{1ef} and μ_{2ef} were calculated graphically by extrapolation of the concentration dependence of summary orientation polarization S_{12} to infinite dilution:

$$S_{12} = \mu_{1ef}^2 x_1 + \mu_{2ef}^2 x_2; \quad (4)$$

$$S_{12} = \mu_{1ef}^2 + (\mu_{2ef}^2 - \mu_{1ef}^2) x_2 = a + bx. \quad (5)$$

Dipole moments $(\mu_{1ef})^2|_{x_2=0}$ and $(\mu_{2ef})^2|_{x_2=0}$ were calculated using the parameters a and b by the equations

$$a = (S_{12})|_{x_2=0} = (\mu_{1ef})^2|_{x_2=0}; \quad (6)$$

$$b = \frac{\partial S_{12}}{\partial x_2} \Big|_{x_2=0} = \mu_{2ef}^2|_{x_2=0} - \mu_{1ef}^2|_{x_2=0}; \quad (7a)$$

$$(\mu_{2ef})^2|_{x_2=0} = (\mu_{1ef})^2|_{x_2=0} + b. \quad (7b)$$

Taking into account that at infinite dilution $\varepsilon_{12}|_{x_2=0} = \varepsilon_1$, dipole moments of the components 1 and 2 were defined by

$$\mu_1 = (\mu_{0,1}^2 \cdot g_1)^{1/2} = \frac{3(\mu_{1ef}^2|_{x_2=0})^{1/2} (2\varepsilon_1 + n_1^2)}{(n_1^2 + 2)(2\varepsilon_1 + 1)}; \quad (8)$$

$$\mu_2 = (\mu_{0,2}^2 \cdot g_2)^{1/2} = \frac{3(\mu_{2ef}^2|_{x_2=0})^{1/2} (2\varepsilon_1 + n_2^2)}{(n_2^2 + 2)(2\varepsilon_1 + 1)}. \quad (9)$$

Using the results of the measurement of permittivity and density of the water used as a solvent, the dipole moment of liquid water molecule μ was calculated by Onsager formula [8]:

$$\frac{(\varepsilon - n^2)(2\varepsilon + n^2)}{\varepsilon(n^2 + 2)^2} = \frac{4\pi N_A}{3} \cdot \frac{\rho}{M} \cdot \frac{\mu^2}{3kT}. \quad (10)$$

Here ε , n , ρ , M are dielectric permittivity, refraction index, density and molecular mass of water, respectively.

Refraction indexes of the polymer and solvent were determined at fixed temperatures

from the molar refraction R_D by

$$R_D = \frac{n^2 - 1}{n^2 + 2} \frac{M}{\rho}. \quad (11)$$

Molar refraction was taken as a sum of atomic refractions and bond increments [12].

PVP monomeric unit molecular mass and molecular refraction were estimated to be $M_{PVP} = 111$ and $R_{DPVP} = 27.445$. Molecular mass and molecular refraction of the hypothetical monomeric unit of PVP + FC₆₀ complex were calculated as average values for a macromolecule containing PVP and FC₆₀ in the proportion of 0.8 mole % FC₆₀ to 100g PVP. Also, using values $M_{FC60} = 720$, $R_{DFC60} = 230.4$ [3] for molecular cluster FC₆₀, values for complex $M_{PVP+FC60} = 111.75$ and $R_{DPVP+FC60} = 29.773$ were obtained.

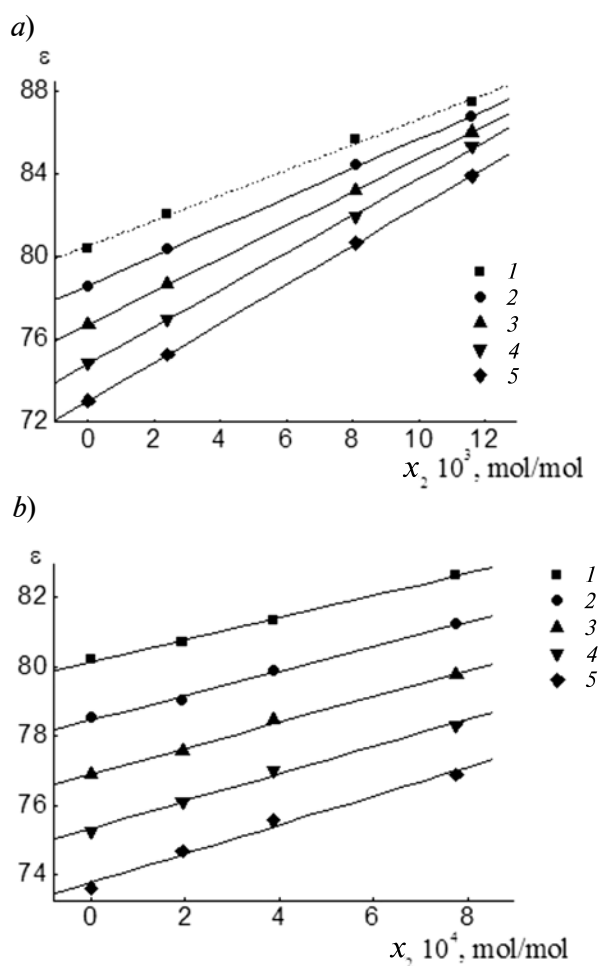


Fig. 1. Dielectric permittivity concentration dependence of PVP (a) and PVP+FC₆₀ (b) aqueous solutions at T °C: 20(1); 25(2); 30 (3); 35(4); 40(5)

Table 1

Temperature dependences of water, PVP and PVP + FC₆₀ characteristics

T °C	v_1 , cm ³ /g	n_1^2	v_2 , cm ³ /g	$n_{2\ PVP}^2$	$n_{2\ PVP+FC60}^2$
20	1.0018	1.7778	0.8333	2.26579	2.40719
25	1.0030	1.7765	0.8343	2.26354	2.40411
30	1.0044	1.7750	0.8353	2.26139	2.40224
35	1.0060	1.7731	0.8363	2.26925	2.39978
40	1.0078	1.7712	0.8373	2.25711	2.39733

Dipole moment estimation total error was $\Delta\mu = \pm 0.05$ D.

Dielectric permittivity concentration dependences for PVP and PVP + FC₆₀ aqueous solutions in the temperature range of 20 – 40 °C are given in Fig. 1. Concentrations used are small enough ($x_2 \leq 1.16 \cdot 10^{-3}$ mole/mole and $x_2 \leq 0.8 \cdot 10^{-3}$ mole/mole respectively) to make it possible to extrapolate ϵ_{12} to infinite dilution situation and to apply dielectric polarization theories for dipole moment calculations.

Molar orientation polarization S_{12} values were calculated by (1) using permittivity (see Fig. 1), specific volume and refraction indexes (Table 1). As an example, Fig. 2 shows concentration dependences of S_{12} for aqueous solutions of PVP and PVP+FC₆₀ at 25 °C. Values

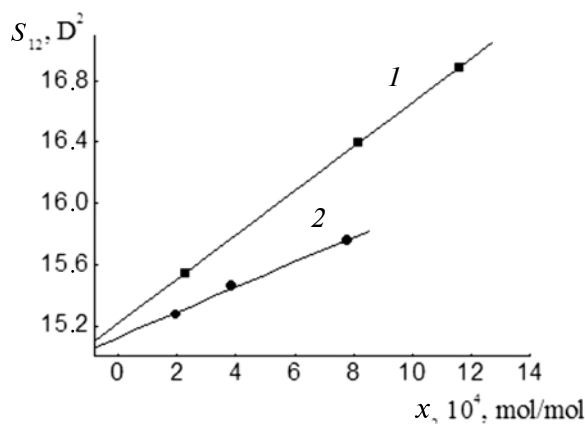


Fig. 2. Molar orientation polarization S_{12} concentration dependence of PVP (1) and PVP + FC₆₀ (2) aqueous solutions at 25 °C

Table 2

Molar orientation polarization S_{12} temperature dependences for PVP and PVP + FC₆₀ aqueous solutions

T °C	PVP			PVP+FC ₆₀		
	$x_2 = 2.27 \cdot 10^{-4}$	$x_2 = 8.14 \cdot 10^{-4}$	$x_2 = 0.00116$	$x_2 = 1.94 \cdot 10^{-4}$	$x_2 = 3.87 \cdot 10^{-4}$	$x_2 = 7.76 \cdot 10^{-4}$
20	15.592	16.344	16.716	15.326	15.464	15.752
25	15.540	16.394	16.880	15.272	15.461	15.754
30	15.483	16.439	17.044	15.261	15.453	15.749
35	15.416	16.481	17.207	15.242	15.439	15.739
40	15.339	16.516	17.222	15.220	15.417	15.723

Table 3

Dipole moment and Kirkwood factor of water in solutions of PVP and PVP + FC₆₀

T °C	Onsager factor (3)	PVP solution				PVP + FC ₆₀ solution			
		$(S_{12}) _{x_2=0}$ (6)	μ_{1ef} (6)	μ_1 (8)	Kirkwood factor (2)	$(S_{12}) _{x_2=0}$ (6)	μ_{1ef} (6)	μ_1 (8)	Kirkwood factor (2)
20	1.254	15.327	3.91	3.12	2.88	15.182	3.89	3.10	2.85
25	1.253	15.216	3.90	3.11	2.86	15.126	3.89	3.10	2.84
30	1.253	15.097	3.89	3.10	2.84	15.113	3.89	3.10	2.84
35	1.252	14.967	3.87	3.09	2.82	15.093	3.89	3.10	2.84
40	1.251	14.879	3.86	3.08	2.81	15.067	3.88	3.10	2.83

Table 4

 Dipole moment and Onsager factor of PVP and PVP + FC₆₀ in the water

T °C	PVP				PVP+FC ₆₀			
	$b = [\partial(S_{12}) / \partial x_2] _{x_2=0}$ (7a)	μ_{2ef} (7b)	Onsager factor (3)	μ_2 (9)	$b = [\partial(S_{12}) / \partial x_2] _{x_2=0}$ (7a)	μ_{2ef} (7b)	Onsager factor (3)	μ_2 (9)
20	1213.2	35.05	1.412	24.8	733.2	27.37	1.456	18.79
25	1438.6	38.13	1.411	27.0	817.3	28.85	1.456	19.82
30	1668.9	41.04	1.410	29.1	827.3	29.02	1.456	19.93
35	1909.0	43.86	1.410	31.1	842.0	29.28	1.456	20.11
40	2017.4	45.08	1.410	32.0	853.0	29.46	1.456	20.24

of S_{12} at $x_2 = 0$, increments of S_{12} concentration dependences and dipole moments per monomer unit for PVP and PVP+FC₆₀ calculated by (2)–(9) are presented in Tables 2 – 4.

Dipole moments and Kirkwood factor temperature dependences of PVP and PVP + FC₆₀ as well as of water and N-methylpyrrolidone (NMP) which is low molecular weight analog of PVP monomeric unit are compared in Fig. 3, 4.

It is significant that the values of dipole moments and Kirkwood factor for liquid water calculated according to Buckingham theory are in good agreement with earlier published values. Thus, calculated dipole moments are to be considered correct and adequate.

Dipole moment and Kirkwood factor temperature dependences were discussed in the previous paper [10]. Dipole moments of NMP in the water (4.12 D) and non-

polar solvents dioxane (4.06 D) and benzene (4.09 D) at 20 °C are close to each other within the experimental error confirming the fact that the NMP molecules do not disturb the local structure of water. The life time of hydrated shell seems to be too short to lead to significant polarization effects.

Dipole moments of macromolecules of PVP and PVP + FC₆₀ are rather large being 25 and 18 D, respectively. It can be seen from Fig. 3 that the dipole moments of PVP increase noticeably with temperature, then reach a plateau of approximately 30 D at 40 °C whereas the dipole moments of PVP + FC₆₀ complex stay nearly constant. We suppose that the groups –N–C=O– located in each monomeric unit near the macromolecule main chain, mostly in *trans*-conformation, determine the formation of helical blocks stabilized by donor-acceptor interactions inside the macromolecular coils.

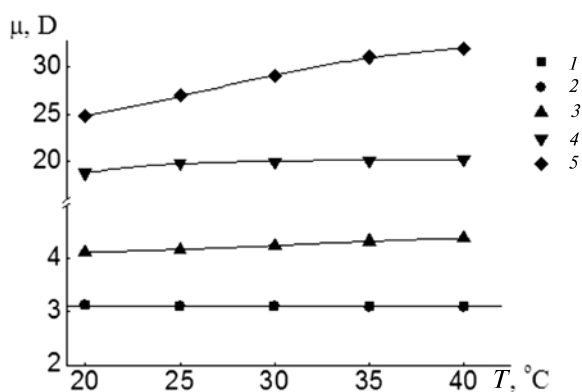


Fig. 3. Dipole moment temperature dependence of water (1, 2) (see also Table 3); N-methylpyrrolidone aqueous solution (3) [11]; PVP + FC₆₀ (4) and PVP (5) (Table 4).

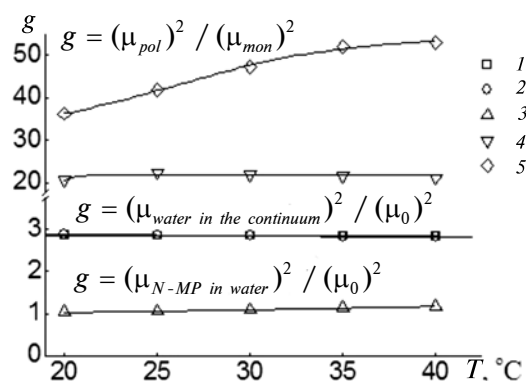


Fig. 4. Kirkwood factor $g = \mu^2 / \mu_0^2$ temperature dependence for water in solutions of PVP and PVP + FC₆₀ at infinite dilution (1, 2); NMP (3) [11], PVP+FC₆₀ (4) and PVP (5) in the water

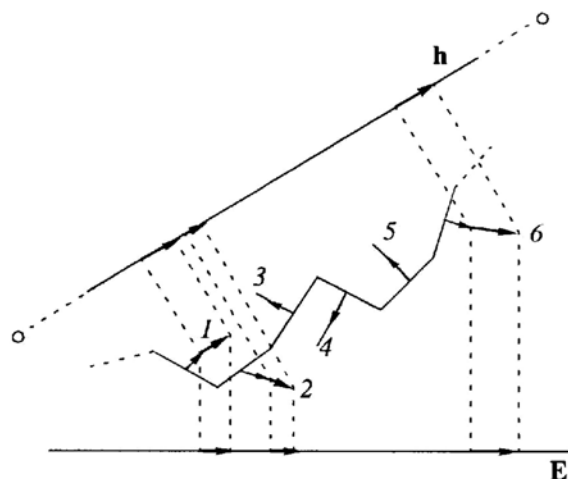


Fig. 5. Formation of non-alternating projections of dipole moment μ on helix axis vector h and electrical field vector E for the chain segment with $-N-C-O-$ group trans-conformation.

Thin arrows depict constant dipole moment of $-N-C=O-$ groups near the main chain, bold arrows – induced dipole moments of these groups in donor-acceptor form directions (1, 2, 6); thin lines – movement fluctuation direction of dipole moments of $-N-C=O-$ groups which do not create induced dipole moments (3, 4, 5)

In this case, non-alternating projection of the $-N^+-C=O^-$ group dipole moment on the helix axis appears in the external electrical field as

depicted in Fig. 5 similar to the matter discussed in [15]. As the temperature rises, hydrophobic interactions tend to become stronger due to H-bonds of hydrophilic segments, and water molecules life time decreases. Further structuring inside the coil takes place because of the helical blocks orientation ordering. Large values of PVP and PVP+ FC_{60} dipole moments in aqueous solutions are determined by induced dipole moments vectorial addition and helical blocks association.

Less values of PVP + FC_{60} complex dipole moment are caused by fullerene molecules implantation into macromolecular coils, which makes helical blocks formation more difficult. In the macromolecular coil of PVP + FC_{60} , complex helical blocks seem to be shorter than in PVP macromolecules. Distinctive for fullerene, donor-acceptor interactions [16] with PVP monomeric units (so called lactam traps) lead to monomeric unit dipole moments compensation, helical blocks shortening and, thus, macromolecule dipole moment decrease. Coordination number of polar groups taking part in correlating orientation can be evaluated by Kirkwood factor (see Fig. 4) as approximately 3 for liquid water, approximately 1 for liquid NMP or NMP aqueous solution, 36 for PVP and 24 for PVP + FC_{60} infinitely diluted aqueous solutions.

REFERENCES

1. Kirsh Yu.E. Poli-N-vinilpirrolidon i drugie poli-N-vinilamidy. Moscow, Nauka, 1998. (rus)
2. Kamalova D.I., Koliadko I.M., Remizov A.B. Konformatsionnye zondy v izuchenii lokal'noi molekuliarnoi dinamiki razvetvlennogo polimetilmetakrilata i ego fullerenosoderzhashchego analoga. XX Vseross. Konf. «Struktura i dinamika molekuliarnykh sistem» i 11-ia Mezhdunarodnaia shkola molodykh uchenykh «Sintez, struktura i dinamika molekuliarnykh sistem». 24-29 iyunia 2013g. ozero Ial'chik. Sb. tez-v, dokl. i soobshch. 106 p. (rus)
3. Khairullin A.R., Stepanova T.P., Rozhkova N.N., Gladchenko S.V., Krakoviak M.G., Anufrieva E.V., Piotrovskii L.B., Anan'eva T.D., Nekrasova T.N. Vodorastvorimye komplekсы fullerena s poli-N-vinilpirrolidonom i sposob polucheniia etikh kompleksov. Patent RF No. 2255942. Opubl. Biul. No. 19. 2005. (rus)
4. Krakoviak M.G., Anufrieva E.V., Anan'eva T.D., Nekrasova T.N. Vodorastvorimye komplekсы poli-N-vinilamidov var'iruemogo stroeniia s fullerenami C_{60} i C_{80} . *Vysokomolekuliarnye soedineniia*, 2006, Series A, Vol. 48, No. 5, pp.1-7. (rus)
5. Moravsky A.P., Fursikov P.V., Kiryakov N.V., Ryabenko A.G. *Mol. Mat.* 1996, Vol. 7, pp. 241-246. (rus)
6. Stepanova T.P., Burshtein L.L. *Izmeritel'naia iacheika*, 1983, No.22. 105 p. (rus)
7. Buckingham A.D. A Theory of the dielectric polarization of polar substances. *Proc. Roy. Soc. A. Mathem. and Phys. Sci.* 1956, Vol. A 38, No. 1213, pp. 235-244.
8. Onsager L. Electrical moments of molecules in liquids. *J. Amer. Chem. Soc.* 1936, Vol. 58, No. 8, pp. 1468-1493.
9. Vol'kenshtein M.V. Stroenie i fizicheskie svoistva molekul. Moscow, Leningrad, Iz-vo AN SSSR, 1955. (rus)
- Stepanova T.P., Karpenko E.D., Kapralova V.M. Dipole moments of N-methylpyrrolidone in liquid state and in dilute aqueous solution. *St. Petersburg*

Polytechnical University Journal: Physics and mathematics, 2013, No. 4-1(182) pp. 112–116. (rus)

11. **Lee C.M., Kumler W.D.** The dipole moment and structure of five- and six- membered lactams. *JACS*, 1961, Vol.83, No. 22, pp.4593–4596.

12. **Frolov V.I., Stepanova T.P., Borisova T.I., Filippova O.E., Khokhlov. A.R.** Dinamika ionnoi atmosfery geli polimetakrilata natriia v metanole v radiochastotnom diapazone. *Vysokomolekuliarnye soedineniia*, 2002, A, Vol. 44, No. 4, pp. 597–604. (rus)

13. **Badamshina E.R., Gafurova M.P.** Modifikatsiia svoistv polimerov putem dopirovaniia fullerenom C_{60} . *Vysokomolekuliarnye soedineniia*, 2008, Seriia B, Vol. 50, No. 8, pp.1572–1584. (rus)

14. **Changchun Wang, Zhi-Xin Guo, Shoukuan Fu, Wei Wu, Daoben Zhu.** Polymers containing fullerene or carbon nanotube structures. *Prog. Polym. Sci.* 2004, No. 29, pp. 1079–1141.

15. **Evlampieva N.P., Lavrenko P.N, Melenevskaia E.Yu., Vinogradova L.V., Ryuntev E.I., Zgonnik V.N.** Molekuliarnye svoistva kompleksov tsiklosoderzhashchikh polimerov s fullerenom C_{60} v rastvorakh. *Fizika tverdogo tela*, 2002, Vol. 44, Iss. 3, pp. 537–540. (rus)

16. **Vinogradova L.V., Melenevskaia E.Yu., Khachaturov A.S.** Vodorastvorimye komplekсы fullerena C_{60} s poli-N-vinilpirrolidonom. *Vysokomolekuliarnye soedineniia*, Seriia A, 1998, Vol. 40, No. 11, p. 1854. (rus)

СПИСОК ЛИТЕРАТУРЫ

1. **Кирш Ю.Э.** Поли-N-винилпирролидон и другие поли-N-виниламиды. М.: Наука, 1998. 252 с.

2. **Камалова Д.И., Колядко И.М., Ремизов А.Б.** Конформационные зонды в изучении локальной молекулярной динамики разветвленного полиметилметакрилата и его фуллереносодержащего аналога // XX Всерос. конф. «Структура и динамика молекулярных систем» и 11-я Международн. школа молодых ученых «Синтез, структура и динамика молекулярных систем». 24 – 29 июня 2013 г. Озеро Яльчик . Сб. тезисов и сообщений. 106 с.

3. **Хайруллин А.Р., Степанова Т.П., Рожкова Н.Н., Гладченко С.,В., Краковяк М.Г., Ануфриева Е.В., Пиотровский Л.Б., Ананьева Т.Д., Некрасова Т.Н.** Водорастворимые комплексы фуллерена с поли-N-винилпирролидоном и способ получения этих комплексов. Патент РФ. № 2255942. Опубл. Бюл. № 19, 2005 г.

4. **Краковяк М.Г., Ануфриева Е.В., Ананьева Т.Д., Некрасова Т.Н.** Водорастворимые комплексы поли-N-виниламидов варьируемого строения с фуллеренами C_{60} и C_{80} . // *Высокомолекулярные соединения*. 2006. Сер. А. Т. 48. № 5. С. 926–932.

5. **Моравский А.П., Фурсиков П.В., Кирьяков Н.В., Рябенко А.Г.** // *Мол. мат.* 1996. Т. 7., 241 с.

6. **Степанова Т.П., Бурштейн Л.Л.** Измерительная ячейка. А.с. № 10232331983. 1983 г.

7. **Buckingham A.D.** A theory of the dielectric polarization of polar substances. *Proc. Roy. Soc. A, Mathem. a. Phys. Sci.* 1956, Vol. A 38, No. 1213, pp. 235–244.

8. **Onsager L.** Electrical moments of molecules in liquids. *J. Amer. Chem. Soc.* 1936, Vol. 58, No. 8, 1468 p.

9. **Волькенштейн М.В.** Строение и физические свойства молекул. М.Л.: Изд-во АН СССР, 1955. 638 с.

10. **Степанова Т.П., Карпенко Е.Д., Капралова В.М.** Дипольные моменты N-винилпирролидона в жидком состоянии и в разбавленном водном растворе // *Научно-технические ведомости СПбГПУ. Физико-математические науки*. 2013. № 4-1 (182). С. 112–116.

11. **Lee C.M., Kumler W.D.** The dipole moment and structure of five- and six- membered lactams. *JACS*, 1961, Vol.83, No. 22, pp. 4593–4596.

12. **Фролов В.И., Степанова Т.П., Борисова Т.И., Филиппова О.Е., Хохлов А.Р.** Динамика ионной атмосферы гелей полиметилметакрилата натрия в метаноле в радиочастотном диапазоне // *Высокомолекулярные соединения*. 2002. А. Т. 44. № 4. С. 597– 604.

13. **Бадамшина Е.Р., Гафурова М.П.** Модификация свойств полимеров путем допирования фуллереном C_{60} . // *Высокомолекулярные соединения*. 2008. Сер. Б. Т. 50. № 8. С. 1572–1584.

14. **Changchun Wang, Zhi-Xin Guo, Shoukuan Fu, Wei Wu, Daoben Zhu.** Polymers containing fullerene or carbon nanotube structures. *Prog. Polym. Sci.* 2004, No. 29, pp. 1079–1141.

15. **Евlampieva Н.П., Лавренко П.Н., Меленеvская Е.Ю., Виноградова Л.В., Рюмцев Е.И., Згонник В.Н.** Молекулярные свойства комплексов циклосодержащих полимеров с фуллереном C_{60} в растворах // *Физика твердого тела*. 2002. Т. 44. Вып. 3. С. 537–540.

16. **Виноградова Л.В., Меленеvская Е.Ю., Хачатуров А.С.** Водорастворимые комплексы фуллерена C_{60} с поли-N-винилпирролидоном // *Высокомолекулярные соединения*. 1998. Сер. А. Т. 40. № 11. С. 1854.

СТЕПАНОВА Тамара Павловна – кандидат физико-математических наук, старший научный сотрудник Института высокомолекулярных соединений РАН.

199004, Россия, г. Санкт-Петербург, Большой пр. В.О., 31

t_stepanova2005@mail.ru

АНАНЬЕВА Татьяна Дмитриевна – кандидат химических наук, старший научный сотрудник Института высокомолекулярных соединений РАН.

199004, Россия, г. Санкт-Петербург, Большой пр. В.О., 31

anthracene@hq.macro.ru

КАРПЕНКО Елена Драгановна – студентка Санкт-Петербургского государственного политехнического университета.

195251, Россия, г. Санкт-Петербург, Политехническая ул., 29.

ele62461401@yandex.ru

КАПРАЛОВА Виктория Маратовна – кандидат физико-математических наук, доцент кафедры интегральной электроники Санкт-Петербургского государственного политехнического университета.

195251, Россия, г. Санкт-Петербург, Политехническая ул., 29.

kapralova2006@yandex.ru