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SIX-COORDINATE COMPLEXES OF NITROSYL IRON-PORPHYRINS WITH TRANS DMSO LIGAND

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By consecutive low-temperature reaction of DMSO and NO with sublimed microporous layers of Fe(Por) (Por - meso-tetraphenyl- and meso-tetra-p-tolyl-porphyrinato dianions) the mixed-ligand Fe(Por)(DMSO)(NO) complexes were partly obtained as was demonstrated by FTIR spectroscopy with supporting data provided by using ¹⁵NO and DMSO-d₆ isotopomers. Formation of the Fe(Por)(DMSO)(NO) by the interaction of DMSO with Fe(Por)(NO) in low-temperature dichloromethane solution is almost quantitative. From the temperature dependence of the equilibrium constants thermodynamic parameters of complexation reaction were determined. FTIR data indicate coordination of DMSO through a sulfur atom, while DFT calculations performed with porphine at room temperature give some lower energy value for the O-bound species.

Figs. 5, tables 2, references 11.

The enormous physiological role of nitrogen oxide (NO) in many cases is connected to its interaction with *heme* proteins [1] including those with the *trans* methionine ligand. In the conditions of oxidative stress the oxidation of methionine to corresponding sulfoxide is possible. Therefore, it was of a great interest to examine whether the 6-coordinate nitrosyl complexes of Fe-porphyrins with *trans* dimethylsulfoxide ligand can exist and, if so, with which atom, sulfur or oxygen, it will be coordinated in these species [2]. In the complexes with transition metals both types of complexes are known. Moreover, in the same complex with two or more sulfoxides one of them may be bound through the sulfur atom while the other one through the oxygen atom [2, 3].

Sulfoxide group contains sigma S- and O-donor atoms as well as π -electrons that also can potentially enter into donor-acceptor interaction with transition metal.

While 6-coordinate Fe(II) porphyrin nitrosyl complexes with axial N-donors have been extensively studied as a model for an axial histidine ligation of hemoglobin and myoglobin [1], much less attention has been focused on the effect of axial S- and O-donor ligands. Ferrous NO adduct of myoglobin H93G cavity mutant ligated by thioether (THT) has been prepared by Dawson et al. [4], and studied by UV-vis and magnetic CD spectroscopy. The interaction of nitrosyl(protoporphyrin IX dimethyl esther)iron(II) with various sulfur and oxygen donor ligands was studied at low temperatures by Yoshimura using EPR spectroscopy [5]. The same technique was used recently by Lehnert et al. in examination of thiophenolates and thioether coordination to Fe(tetraphenylporphyrin)NO center [6]. The interaction of nitrosyl(*meso*-tetraphenyl)- and nitrosyl(*meso*-tetra*-p*-tolyl)-porphyrinato iron(II) with various sulfur and oxygen donor ligands was studied by Martirosyan et al. using low-temperature FTIR and optical absorption spectroscopy [7].

Experimental Section

The iron(II) porphyrinates Fe(Por) (Por – *meso*-tetraphenyl- and *meso*-tetra-*p*-tolyl- porphyrinato (TPP and TTP correspondingly) dianions) are very sensitive to oxygen and are readily oxidized. For this reason the more stable hexa-coordinate complexes $Fe(Por)(B)_2$ with nitrogen bases (B is Py or piperidine) were used as the precursors to prepare sublimed layers. The complexes $Fe(Por)(B)_2$ were synthesized according to published method [8].

Then, as done previously [7], the parent complexes were introduced into the Knudsen cell of the high vacuum system and heated at 490 K for $\sim 2 h$ until the vacuum gauge indicated complete dissociation of the axial ligand. The resulting Fe(Por) was sublimed from the Knudsen cell at \sim 520 K and deposited on a KBr of the optical cryostat. NO (¹⁵NO) was purified by passing it through KOH pellets and a cold trap (dry ice/acetone) to remove the higher nitrogen oxides and trace quantities of water. The purity was checked by IR measurements of the layer obtained by slow deposition of NO onto the cold substrate of the optical cryostat (77 K). The IR spectrum did not show the presence of N_2O , N_2O_3 or H_2O . ¹⁵NO with 98.5% enrichment was purchased from the Institute of Isotopes, Republic of Georgia, and was purified by the same procedure. Sublimed layers of Fe(Por) were obtained on the cold (77 K) KBr support of an optical cryostat according to the published procedure [7]. Then the layer was warmed till 200 K under dynamic vacuum, DMSO was introduced into the cryostat and the layer was slowly warmed to the room temperature. FTIR spectra demonstrated the complete shifts of some of the porphyrin bands.

The interaction of DMSO with Fe(Por)(NO) in dichloromethane solution was carried out in the optical cryostat provided with the 0.05 cm CaF₂ cell. A measured quantity of Fe(Por)(NO) was fed into the airtight flask provided with septum. Known quantities of previously degassed solutions of DMSO in dichloromethane were transferred into this flask by vacuum techniques. The solutions thus prepared

were transferred to an IR cell using an airtight Hamilton syringe. The cell was then tightly closed and placed into the cryostat. The cell was then cooled using liquid nitrogen vapors and the FTIR spectra were taken at temperatures controlled by a thermocouple that was in close contact with the cell. By changing the flow rate of the liquid nitrogen it was possible to maintain the temperature of solution at a given temperature (± 1 °C).

The FTIR spectra were acquired on a Nexus (Thermo Nicolet Corporation) in the spectral range of 400-4000 cm^{-1} with a resolution of 4 cm^{-1} . All density functional theory (DFT) calculations were performed at unrestricted TPSSTPSS/DGDZVP level of theory without symmetry constraints using Gaussian 09 package.

Results and discussion

In sublimed layers two types of experiments were carried out with the goal to obtain the mixed nitrosyl complex with *trans* sulfoxide ligand. In the first type of experiments the sulfoxide vapors were introduced into the cryostat containing the nitrosyl complexes of Fe(Por)(NO) that were obtained by interaction of NO gas with microporous layers of Fe(Por). Cooling of the layer does not lead to appearance of a new v(NO) band that could be indicator of mixed complex formation. At low-temperatures when such a complex could be stable the mobility of DMSO in the layer is too low to provide the penetration of sulfoxide in the bulk of the layer.

In the second type of experiments the layers of iron-porphyrins were initially introduced under the vapors of DMSO. According to the changes in the FTIR spectra this procedure leads to the formation of iron-porphyrins 5- and 6-coordinate complexes Fe(Por)(DMSO)_{1,2}, in which 5-coordinate species are in the high-spin, while 6-coordinate complexes are in the low-spin state. In Fig. 1 the FTIR spectrum of Fe(TPP) is demonstrated before and after interaction with the very small quantities of DMSO vapors. This procedure leads to the appearance of new bands that are certainly associated with the presence of coordinated DMSO ligand. DMSO is ambidentate ligand and can be coordinated with the metal both through the oxygen and sulfur atom. IR spectroscopy is a powerful tool for distinguishing these two possibilities. Coordination through the sulfur to the increased frequency of the sulfoxide bond relative to v(S=O) of free ligand. As it is seen in Fig. 1 the new band at 1109 cm^{-1} appeared that is shifted to higher frequency in regard to the band of free ligand at ~1060 cm^{-1} .



Fig. 1. FTIR spectral changes upon interaction of DMSO vapors (0,1 *torr*) with sublimed layers of Fe(TPP) (solid line) in temperature range 230-270 *K*.

The porphyrin vibrations provide additional insight into the electronic structure of the new complexes [9]. A band in the vicinity of 1350 cm^{-1} representing the porphyrin core mode corresponding to $v(C_a-C_m)$ mixed with some $v(C_m$ -phenyl) lies at higher frequencies for low-spin complexes. Similarly, a low-energy porphyrin core deformation mode occurs in the range of 450 cm^{-1} . For the low-spin iron-porphyrin complexes it is located in the 460 cm^{-1} range while for high-spin species it shifts to 430 cm^{-1} . From Fig. 2 it is seen that the band at 1346 cm^{-1} that is characteristic for the intermediate state after interaction with more quantities of DMSO splits into 2 bands at 1350 and 1336 cm^{-1} (solid line). First one is observed in the range characteristic for the low-spin complexes and belongs to Fe(TTP)(DMSO)₂, while the second one at 1336 cm^{-1} is characteristic for the high-spin complex.

Evacuation of the cryostat supports these assignments (Fig. 2, dashed and dotted spectra). Together with diminishing of the bands of coordinated and free DMSO, in the range of spin- sensitive bands the band at 1350 cm^{-1} loses intensity and undergoes some low-frequency shift while band at 1336 cm^{-1} grows in intensity. This is the evidence of Fe(TTP)(DMSO)₂ decomposition to Fe(TTP)(DMSO) and Fe(TTP).



Fig. 2. FTIR spectral changes upon high-vacuum evacuation of DMSO for the layer containing mostly Fe(TTP)(S-DMSO)₂ (solid line) during 10 (dashed line) and 30 (dotted line) min.



R - phenyl, p-tolyl

Addition of NO into the cryostat at 200 K leads to appearance of two new bands in the range of nitrosyl stretching frequencies (Fig. 3) that are summarized in Table 1 together with data for ¹⁵NO species. The values of isotopic shifts certainly indicate that they belong to nitrosyl stretching v(NO) of coordinated NO in iron-porphyrin complexes. Band at 1674 cm^{-1} belongs to 5-coordinate nitrosyl complex Fe(Por)(NO) while the band at 1637 cm^{-1} should be assigned to coordinated NOgroup in 6-coordinate species with *trans* sulfoxide ligand, as is demonstrated in Scheme 2.

Table 1

v(NO) (v(¹⁵NO)) in 5-coordinate nitrosyl complexes of Fe(Por) and 6-coordinate nitrosyl complex with *trans* dimethylsulfoxide ligand.

Complex	υ(NO)	$\upsilon(^{15}NO)$
Fe(TPP)(NO)	1674	1645
Fe(TTP)(NO)	1676	1646
Fe(TPP)(NO)(DMSO)	1636	1607
Fe(TTP)(NO)(DMSO)	1637	1608

TPSSTPSS **B**3LYP Complex 3D model $\Delta E, kcal/mol$ ΔE , kcal/mol E, au E, au Fe(P)(NO)(S-DMSO)_doublet -2935,46974 2 -2935,19158 3 Fe(P)(NO)(S-DMSO) quartet 25 -2935,43299 Fe(P)(NO)(S-DMSO)_sextet -2935,19646 0 -2935,47252 0 Fe(P)(NO)(O DMSO)_doublet Fe(P)(NO)(O DMSO)_quartet -2935,43264 25 Fe(P)(NO)(O-DMSO) sextet

DFT computations for iron-porphine dimethylsulfoxide-nitrosyl complexes coordinated through the S and O atoms in different spin-states



Fig. 3. FTIR spectral changes observed upon interaction of 3 torr NO with layer containing $Fe(TTP)(DMSO-d_6)_2$ in the temperature range 200-210 K.

Scheme 2



Hence NO can substitute DMSO ligand from $Fe(Por)(DMSO)_2$ to form Fe(Por)(NO)(DMSO) and Fe(Por)(NO). The attempt to obtain only 6-coordinate mixed ligand complex in the solid state was not successful. However, this complex almost quantitatively was possible to obtain in the solution upon decreasing its temperature (Fig. 4). In these experiments DMSO ligand was added to solution of Fe(Por)(NO) in dichloromethane and the temperature of solution was gradually decreased. This led to spectral changes represented in Fig. 4. At these conditions 5-coordinate complex Fe(Por)(NO) almost completely was transferred to the 6-coordinate mixed ligand complex Fe(Por)(NO)(DMSO). From these data the thermodynamic parameters and equilibrium constant of the reaction

 $Fe(Por)(NO) + DMSO \leftrightarrow Fe(Por)(NO)(DMSO)$

were estimated, that in the case of Fe(TTP) are equal to $\Delta H = -11.3 \pm 0.2 \ kJ \cdot mole^{-1}$, $\Delta S = -66 \pm 2 \ J \cdot mole^{-1} \cdot K^{-1}$, $\Delta G = +8.6 \pm 0.2 \ kJ \cdot mole^{-1}$ and $K_{298} = 3 \cdot 10^{-2}$.



Fig. 4. Temperature dependence of the FTIR spectra in the u(NO) range of the Fe(TTP)(NO) dissolved in the DMSO/CH₂Cl₂ solution.

DMSO is ambidentate ligand. In the 5- and 6-coordinate sulfoxide complexes of iron-porphyrins, as it was shown above, it is coordinated through the sulfur atom. The same is taking place in the mixed ligand Fe(Por)(NO)(DMSO) complexes. Since the rocking vibration of methyl group $\rho(CH_3)$ [2] in DMSO is disposed in the range of 950 cm⁻¹, in which the v(S=O) of O-coordinated sulfoxide is expected to occur, in order to be sure that there is no new band in this spectral range the experiments were performed also with DMSO-d₆. Rocking vibration of CD₃ groups is observed at much lower frequency and this spectral range is empty.



Fig. 5. FTIR spectra of the sublimed layer of Fe(TTP) (solid line), Fe(TTP)(DMSO-d₆)(NO) + Fe(TTP)(NO) (dashed line) and Fe(TTP)(DMSO)(NO) + Fe(TTP)(NO) (dotted line) at 205 K. 470

The absence of a new band in this spectral range upon formation of the mixed ligand Fe(Por)(NO)(DMSO) complexes (Fig. 5, dashed line) is an evidence that in this complex also sulfoxide is coordinated through the sulfur atom. Hence oxidation of methionine to sulfoxide both in complexes with sulfoxide and mixed ligand complexes with NO will leave sulfur atom coordinated with Fe(II). It means, that upon oxidation of proximal methionine to sulfoxide *heme* environment would not be subjected to significant changes.

It should be noted that computations give some lower energy for the Ocoordinated DMSO ligand in the mixed ligand Fe(Por)(NO)(DMSO) complexes, so there is some discrepancy between experimental results and computations. However, it is necessary to stress that the computations were performed in the gas phase at room temperature. Calculation of both TPP and porphine (Table 2) 6-coordinate complexes favor O-coordinated DMSO by ~2 *kcal/mol*. Unfortunately, these compounds are not stable at room temperature and at this moment it seems rather difficult to evaluate the coordination mode of DMSO at 298 *K*. However, one must not rule out the possible isomerization following the increase in temperature.

In all cases warming of the layer to room temperature under high vacuum leads to slow elimination of the DMSO ligand. In the case of 5- and 6-coordinate DMSO complexes it results in the formation of the 4-coordinate Fe-porphyrin complexes, while in the case of mixed ligand Fe(Por)(NO)(DMSO) complexes it comes to the end with the formation of thermodynamically very stable nitrosyl complex Fe(Por)(NO).

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ՆԻՏՐՈԶԻԼ ԵՐԿԱԹ ՊՈՐՖԻՐՆՆԵՐԻ 6 -ԿՈՈՐԴԻՆԱՑՎԱԾ ԿՈՄՊԼԵՔՍՆԵՐԸ ՏՐԱՆՍ ԴԻՄԵԹԻԼՍՈՒԼՖՕՔՍԻԴԱՅԻՆ ԼԻԳԱՆԴԻ ՒԵՏ

Ա. Ա. ՏՈՎՏԱՆՆԻՍՅԱՆ, Ա. Վ. ԻՐԵՑԿԻ և Տ. Ս. ԿՈԻՐՏԻԿՅԱՆ

Երկաթ-պորֆիրինների (Fe(Por), Por- մեզո-տետրաֆենիլ- և մեզո-տետրա-թ-տոլիլպորֆիրինատո դիանիոն) միկրոծակոտկեն սուբլիմված թաղանթների Հետ դիմեթիլսուլֆօքսիդի (DMSO) և ազոտի մոնօքսիդի (NO) Հաջորդաբար փոխազդեցությամբ ցածր ջերմաստիճաններում մասնակիորեն ստացվել են իատը-լիգանդային Fe(Por) (DMSO)(NO) կոմպլեքսներ, ինչպես ցույց է տրված ՖՁԻԿ սպեկտրաչափության եղանակով, որոնք լրացուցիչ Հիմնավորվում են 15NO և DMSO-d6 իզոտոպոմերների կիրառմամբ:

Fe(Por)(DMSO)(NO)-ի գոյացումը DMSO-ի փոխաղդեցու[ժյամբ դիքլորմեԹանում լուծված Fe(Por)(NO)-ի Հետ գրեԹե քանակական բնույ[ժ է կրում: Հավասարակչռու[ժյան Հաստասոունի ջերմաստիճանային կախվածու[ժյունից Հաչվարկվել են կոմպլեքսագոյացման ռեակցիայի Թերմոդինամիկ պարամետրերը: ՖՁԻԿ սպեկտրաչափական տվյալները խոսում են այն մասին, որ DMSO-ն կոորդինացիայի մեջ է մտնում երկաԹի Հետ ծծումբի ատոմի միջոցով: Միևնույն ժամանակ Հաչվարկները կատարված խտու[ժյունների ֆունկցիոնալ տեսու[ժյան չրջանակներում դազ ֆազայում և սենյակի ջերմաստիճաններում քիչ ավելի խոր էներդիայի մինիմում են դրսևորուն Օ-կապված իղոների Համար:

ШЕСТИКООРДИНАЦИОННЫЕ НИТРОЗИЛЬНЫЕ КОМПЛЕКСЫ Fe-ПОРФИРИНОВ С *ТРАНС* ДИМЕТИЛСУЛЬФОКСИДНЫМ ЛИГАНДОМ

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Последовательное взаимодействие DMSO и NO с микропористыми слоями Fe(Por) -ов (Por – *мезо*-тетра-фенил- и *мезо*-тетра-*р*-толил-порфиринато дианионы) при низких температурах ведет к частичному образованию смешанного комплекса Fe(Por)(DMSO)(NO), как об этом свидетельствуют Фурье-ИК-спектры, подкрепленные данными с изотопными ¹⁵NO и DMSO-d₆. Образование при низких температурах Fe(Por)(DMSO)(NO) взаимодействием DMSO с растворенным в дихлорметане нитрозильным комплексом Fe(Por)(NO) носит почти количественный характер. Из температурной зависимости константы равновесия реакции комплексообразования вычислены термодинамические параметры этого процесса. Согласно данным Фурье-ИК-спектроскопии в смешанном комплексе DMSO координирован с железом через атом серы. В то же время расчеты по теории функционала плотности в газовой фазе и при комнатных температурах дают несколько более глубокий минимум для O-связанного изомера.

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