

Computational and QSAR study of the alkylnaphthyl ketones adsorption on silver-ion stationary phase

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Abstract The chromatographic behaviour of α - and β -alkylnaphthyl ketones at different temperatures on the silver-loaded stationary phase is described based on the QSRR model. Complexation *via* an oxygen atom is favoured over the interaction through the aromatic fragment. The QSRR model and DFT/MP2 studies suggest that retention times of alkylnaphthyl ketones on silver-containing stationary phases are determined primarily by the dipole moment, length of the alkyl substituent and concentration of modifier in the mobile phase.

Keywords Adsorption · DFT and *ab initio* calculations · QSRR · Silver-ion chromatography

Introduction

Complexation of transition metals with organic ligands have attracted considerable attention within the last decades, since the interactions metal cation – π -system are of great importance in biology, and material chemistry as well as in molecular recognition and guest-host chemistry [1].

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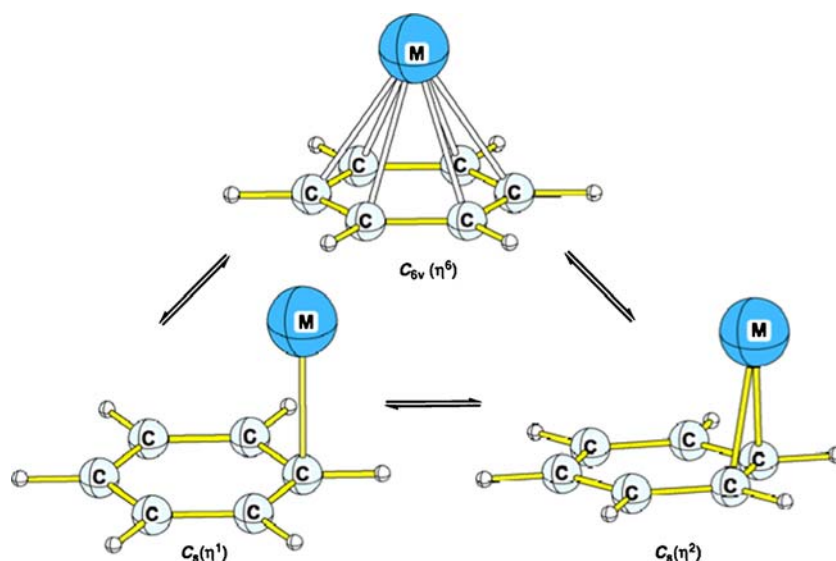
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The metal cation/benzene complexes viewed as a prototype of the (001) graphite surface, may resemble the organic thin films on various metal surfaces, and serve as a “gas-phase” model for surface effects [2]. Silver ion reversible chromatography, that is based on the complexation of Ag^+ with unsaturated compounds forming weakly complexes, has become a core method for the analysis and separation of lipids (especially of triacylglycerols), terpenes and aromatic compounds [3–6].

Over the years many studies were focused on complexation of various metal cations (Cu^+ , Ag^+ , Au^+ , *etc.*) with benzene [7–10]. The binding energy between Ag^+ and benzene lies within 1.31 – 2.39 eV range and depends on the experimental/theoretical method employed. While Dargel *et al.* [11] reported that η^1 (C_s , atop coordination to carbon atom) and η^2 (C_s , bridge coordination between two carbon atoms) are energetically equal based on BLYP and B3LYP calculations, Koch reported preference for the η^6 binding mode (B3LYP) (Scheme 1). In contrast to the DFT the MP2/6-31G(d) computations suggest preferential η^6 coordination [12].

In contrast the complexations of metal cations (especially, Ag^+) with aromatic π -systems different from benzene have been investigated only a little. The DFT and MP2 studies have been reported for the Cu^+ /Ph–X and Li^+ /Ph–X ($X = \text{OH}, \text{NH}_2, \text{CHO}, \text{COOH}, \text{CF}_3$) systems [13] as well as for Cu^+ with various 1,3,5-tri-substituted benzenes [7]. Extensive first principle calculations on the adsorption of naphthalene tetracarboxylic dianhydride on $\text{Ag}(110)$ [14], displayed that bonding is determined by the attraction of negatively charged carboxyl oxygens and positively charged silver atoms. Damyanova *et al.* [15] computed the Ag^+ interactions with various unsaturated carboxylic acids, aldehydes, carboxamides as well as with unsaturated fatty acid esters with one and two isolated C=C double bonds in the gas and condensed phases. Authors concluded

Scheme 1 Different coordination sites of M^+ -benzene



that “the metal ion interacts with both double bonds and carbonyl oxygen, and position of double bond and the chain length has significant impact on such interaction” [15]. The effects of the substituent on the complexation of polycyclic aromatic hydrocarbons with Ag^+ have been studied by the electrospray mass-spectrometry and B3LYP/LANL2DZ calculations [16]. The formation of various complexes between Ag^+ and hydrocarbons, *e.g.*, *via* the carbonyl oxygen and a *peri*-carbon, as well as complexation with one ring carbon or bridging between two ring carbons were found. Unfortunately, the complexation energies have not been reported [16].

The quantitative structure-(chromatographic) retention relationships (QSRR), method describes the relationship between the molecule structure and chromatographic behaviour quantitatively [17–19]. It is useful for pharmacy, organic, analytical and applied chemistry [20, 21], for prediction of the retention times of previously unknown compounds, identification of their separation mechanisms, calibrating of the chromatographic columns and assessing the relative biological activity of molecules.

Method QSRR in liquid chromatography verifies the molecular characteristics that define the retention times of compounds through the correlation with certain retention factors (k), described by various descriptors (P_i) as the following:

$$k = f(P_i) \quad (1)$$

Out of a variety of parameters P_i , the ones that show the best correlation reveal the main factors that control the complexation with stationary phase and help to study the mechanism of adsorption.

Significant numbers of parameters P_i previously were used in QSAR for screening the biologically active compounds.

Usually, physical or chemical (hydrophobicity constant π) and topological (volume and area of molecules, length of substituents) as well as electronic (Hammett's constant σ , *etc.*) descriptors are significant.

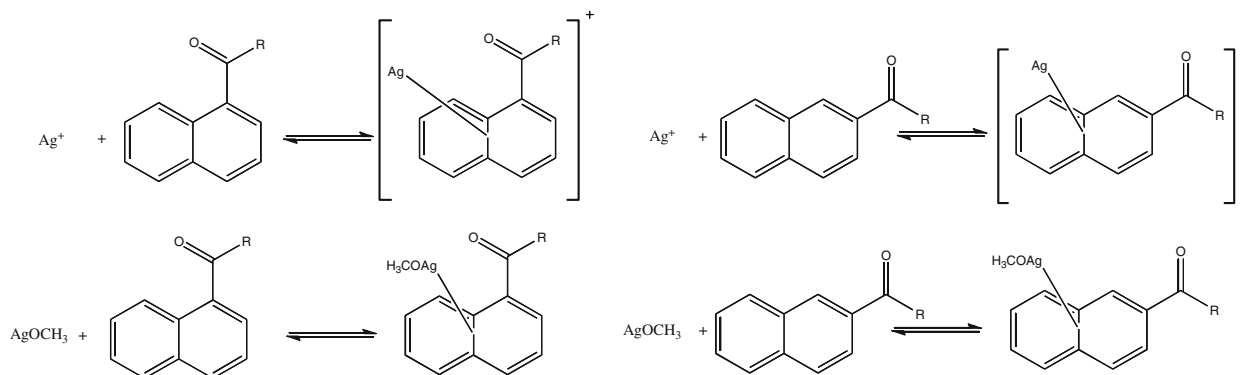
High performance liquid chromatography on silver-containing stationary-phases was applied to various classes of compounds that can form complexes with silver and especially useful in food chemistry and pharmacology [22, 23]. For example, the alkylnaphthyl ketones as models due to the competition between hard (oxygen atom) and soft (double bonds) centres, resemble the bonding situation that is quite often observed in metalcomplex catalysis and is in metalloenzymatic transformation [24]. Thus, for alkylnaphthyl ketones adsorbed on silver-containing stationary-phases two types of complexes may exist, *e.g.* *via* an oxygen atom and *via* the aromatic ring. It was found, however, that the correlation between the retention times and computed complexation energies are poor without involving the solvation effects.

Thus, taking into consideration the importance of the studies on the metal- π interactions and absence of the data for the competitive complexation of $Ag(I)$ with alkylnaphthyl ketones, we now apply the combined DFT/MP2 and QSRR study on this problem.

Methods

All geometries were optimized at B3LYP [25], B3PW91 [26] and MP2 [27] levels of theory with LANL2DZ and DZVP basis sets with Gaussian 03 program package [28]. Stationary points were characterized by frequency analysis within harmonic approximation. The DFT and MP2 computed energies were corrected for zero-point vibrational

energies (ZPVE). The complexation energies were computed using the following model equations [29, 30]:

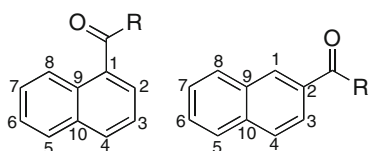


As the descriptors for the alkylnaphthyl ketones the B3LYP/LANL2DZ and MP2/DZVP energies of HOMO and LUMO (E_{HOMO} , E_{LUMO}), the HOMO-LUMO gap (E_{gap}), dipole moments (D) and the molecular volumes (V), as well as the number of carbon atoms in substituent R were used. Due to the fact that retention times of the alkylnaphthyl ketones decrease with the length of the alkyl fragment, $1/R$ was used in the correlation equations. Followed by the multiple linear regression analysis, the rejections of the insignificant equation terms were based on t -test and rejections of correlation coefficients were based on Fisher test. For the comparative analysis of calculated and experimental results retention times of alkylnaphthyl ketones on silver-containing stationary-phase (silver methyl/benzyl sulfonate on silica gel) were used [31].

Results and discussion

Descriptors (E_{HOMO} , E_{LUMO} , E_{gap} , D and V) for the QSRR-procedure were obtained from the DFT and MP2 calculations on the α - and β -substituted alkylnaphthyl ketones **a** and **b** (Scheme 2).

The experimental retention times of model compounds at different concentrations of modifier (isopropanol 0.045, 0.060 and 0.075%) in heptane as a mobile phase at four



R: $-\text{C}_2\text{H}_5$, $-\text{C}_3\text{H}_7$, $-\text{C}_4\text{H}_9$, $-\text{C}_7\text{H}_{15}$, $-\text{C}_9\text{H}_{19}$, $-\text{C}_{11}\text{H}_{23}$

Scheme 2 The α - (**a**) and β - (**b**) alkylnaphthyl ketones used in QSRR study

temperatures (293.15, 303.15, 313.15 and 323.15 K) were used for correlations [31]. To verify the validity of the equations the two compounds (β -ethylnaphthyl ketone and α -heptylnaphthyl ketone) were selected, to verify the predictability of thus obtained QSRR models (Table 1).

Correlations were first performed for the given concentration of modifier based on a number (8 – 10) of the test data points (see Table 1 and 2). After that, for all 12 experimental conditions (three concentrations and four different temperatures) Eq. 2 was obtained (separately for DFT and MP2 descriptors):

$$t_{pred} = const + a_1 \cdot E_{HOMO} + a_2 \cdot E_{LUMO} + a_3 \cdot \frac{1}{R} + a_4 \cdot D \quad (2)$$

where

- E_{HOMO} the energy of the highest occupied molecular orbital of ketone, eV
- E_{LUMO} the energy of the lowest unoccupied molecular orbital of ketone, eV
- R number of carbon atoms in a side chain and
- D computed dipole moment.

After the rejection of all non-valid parameters based on the Fisher test, Eq. 2 transformed to Eq. 3:

$$t_{pred} = const_1 + a_1 \cdot \frac{1}{R} + a_2 \cdot D \quad (3)$$

where $const_1$ – equation constant for specific concentration of modifier.

The relative errors of our predictions for selected compounds did not exceed 5% and, therefore, Eq. 3 seems to be satisfactory. All coefficients of Eq. 3, as well as their

Table 1 Experimental retention times (t_{exp} , min) of α -, β - substituted alkyl naphthyl ketones; modifier – isopropanol; temperature $T_1=293.15\text{K}$, $T_2=303.15\text{K}$, $T_3=313.15\text{K}$, $T_4=323.15\text{K}$

n-Alkyl	Concentration of isopropanol in heptane (vol. %)											
	0.045				0.06				0.075			
	T_1	T_2	T_3	T_4	T_1	T_2	T_3	T_4	T_1	T_2	T_3	T_4
α -C ₂ H ₅ -	30.05	34.38	38.58	41.54	19.66	23.05	26.70	29.75	9.11	10.67	12.25	14.23
β -C ₂ H ₅ -	35.26	40.04	44.56	47.68	22.99	26.72	30.78	34.12	10.41	12.17	13.95	16.23
α -C ₃ H ₇ -	25.71	29.80	33.54	36.28	16.77	19.82	23.01	25.85	8.02	9.07	10.49	12.17
α -C ₄ H ₉ -	23.56	27.07	30.63	33.08	15.07	17.94	20.99	23.64	7.36	8.16	9.49	11.00
β -C ₄ H ₉ -	25.11	29.30	33.24	35.96	16.21	19.36	22.69	25.65	7.79	8.69	10.16	11.86
β -C ₇ H ₁₅ -	19.64	22.98	26.47	29.27	12.69	15.23	18.08	20.71	6.46	7.02	8.21	9.64
α -C ₉ H ₁₉ -	17.68	20.40	23.41	25.84	11.44	13.60	16.04	18.29	6.05	6.44	7.44	8.62
β -C ₉ H ₁₉ -	-	-	24.39	27.06	-	-	16.64	19.15	-	-	-	8.97
α -C ₁₁ H ₂₃ -	16.77	19.57	22.47	25.02	11.00	12.94	15.24	17.63	5.86	6.20	7.12	8.22
β -C ₁₁ H ₂₃ -	-	20.09	23.31	26.14	-	-	15.76	18.39	-	-	7.31	8.54
Reference compounds												
β -C ₃ H ₇ -	28.56	33.06	37.18	40.19	18.55	21.93	25.45	28.61	8.74	9.87	11.46	13.37
α -C ₇ H ₁₅ -	19.01	22.04	25.27	27.78	12.28	14.63	17.27	19.67	6.32	6.81	7.89	9.19

corresponding correlation coefficients are collected in Tables 3 and 4.

Such good correlation based on Eq. 3 leads to the conclusion that the adsorption of alkyl naphthyl ketones on silver-containing stationary phase is determined by structural rather than electronic factors. In accordance with Eq. 3, the retention times of the alkyl naphthyl ketones increase with polarization of the molecule and dipole moment, and decrease with the length of the alkyl fragment. It can be assumed that the complexation occurs *via* the

oxygen atom, because in such cases the alkyl fragment is oriented distantly from the surface of the stationary phase. If the formation of the complex would occur *via* an aromatic ring, the substituents would be oriented along the surface of the sorbent, and their bulkiness would not affect the adsorption significantly.

To obtain the more generalized equation, in the correlation equations the concentration of modifiers were taken into account. As a result, 25 different variables were obtained and their combinations were

Table 2 Descriptors based on DFT and MP2 calculations

n-Alkyl	DFT								MP2							
	E_{HOMO} , -eV	E_{LUMO} , -eV	E_{gap} , eV	R	1/R	D, D	V , Å ³	E_{HOMO} , -eV	E_{LUMO} , -eV	E_{gap} , eV	R	1/R	D, D	V , Å ³		
α -C ₂ H ₅ -	6.249	2.179	4.070	2	0.5	3.267	181.0	-8.085	1.361	9.446	2	0.500	3.943	183.7		
β -C ₂ H ₅ -	6.277	2.05	4.227	2	0.5	3.550	181.7	-8.145	1.298	9.443	2	0.500	4.056	184.3		
α -C ₃ H ₇ -	6.238	2.164	4.074	3	0.333	3.241	198.0	-8.074	1.381	9.455	3	0.333	3.990	200.8		
α -C ₄ H ₉ -	6.236	2.158	4.078	4	0.25	3.309	214.8	-8.068	1.398	9.467	4	0.250	4.010	217.9		
β -C ₄ H ₉ -	6.263	2.030	4.233	4	0.25	3.532	215.6	-8.133	1.311	9.444	4	0.250	4.064	218.2		
β -C ₇ H ₁₅ -	6.258	2.022	4.236	7	0.143	3.534	266.4	-8.127	1.316	9.443	7	0.143	4.081	269.6		
α -C ₉ H ₁₉ -	6.229	2.152	4.077	9	0.111	3.302	299.6	-8.060	1.413	9.474	9	0.111	4.065	303.6		
β -C ₉ H ₁₉ -	6.256	2.020	4.236	9	0.111	3.543	300.3	-8.126	1.318	9.443	9	0.111	4.084	303.9		
α -C ₁₁ H ₂₃ -	6.224	2.124	4.100	11	0.091	3.368	333.5	-8.059	1.414	9.474	11	0.091	4.070	337.9		
β -C ₁₁ H ₂₃ -	6.254	2.020	4.234	11	0.091	3.531	334.1	-8.125	1.319	9.444	11	0.091	4.087	338.2		
Reference compounds																
β -C ₃ H ₇ -	6.269	2.040	4.229	3	0.333	3.538	198.6	-8.137	1.303	9.440	3	0.333	4.063	201.1		
α -C ₇ H ₁₅ -	6.229	2.144	4.085	7	0.143	3.336	265.7	-8.062	1.411	9.473	7	0.143	4.056	269.4		

Table 3 Correlation coefficients (Eq. 3), experimental (t_{exp} , min) and computed (t_{pred} , min) retention times and relative error of prediction (δ ,%) for constant concentration (C) at four temperatures ($T_1=293.15\text{K}$, $T_2=303.15\text{K}$, $T_3=313.15\text{K}$, $T_4=323.15\text{K}$) based on DFT descriptors

Coefficient	T ₁			T ₂			T ₃			T ₄		
	C=0.045			C=0.06			C=0.075			C=0.045		
const	-19.812			-22.602			-16.792			-17.5820		
a ₁	37.758			41.985			47.027			48.116		
a ₂	9.963			11.545			10.434			11.387		
r	0.9888			0.9891			0.9878			0.9896		
r ²	0.9777			0.9782			0.9758			0.9793		
const	-12.483			-14.322			-11.343			-12.564		
a ₁	24.850			28.368			33.088			35.090		
a ₂	6.330			7.433			7.040			8.055		
r	0.9905			0.9904			0.9888			0.9894		
r ²	0.9811			0.9810			0.9777			0.9790		
const	-2.987			-4.610			-4.528			-5.503		
a ₁	9.395			12.581			14.581			17.104		
a ₂	2.380			2.874			3.071			3.622		
r	0.9895			0.9931			0.9923			0.9926		
r ²	0.9895			0.9863			0.9846			0.9852		
Compound	t _{exp}	t _{pred}	δ	t _{exp}	t _{pred}	δ	t _{exp}	t _{pred}	δ	t _{exp}	t _{pred}	δ
	C=0.045											
β-C ₃ H ₇ -	28.56	28.01	1.92	33.06	32.22	2.54	37.18	35.78	3.77	40.19	38.73	3.63
α-C ₇ H ₁₅ -	19.01	18.82	0.1	22.04	21.92	0.54	25.27	24.74	2.1	27.78	27.28	1.8
	C=0.06											
β-C ₃ H ₇ -	18.55	18.19	1.94	21.93	21.42	2.32	25.45	24.58	3.42	28.61	27.63	3.39
α-C ₇ H ₁₅ -	12.28	12.19	0.73	14.63	14.53	0.68	17.27	16.87	2.32	19.67	19.32	1.78
	C=0.075											
β-C ₃ H ₇ -	8.74	8.56	2.06	9.87	9.75	1.22	11.46	11.19	2.18	13.37	13.01	2.69
α-C ₇ H ₁₅ -	6.32	6.29	0.47	6.81	6.78	0.44	7.89	7.80	1.14	9.19	9.03	1.74

used to build the correlation equations. After applying the procedures described above, Eq. 4 was suggested to predict the retention times of six reference compounds (see Tables 5 and 6).

$$t_{pred} = const_2 + a_1 \cdot \frac{1}{R} + a_2 \cdot D + \left(a_3 \cdot \frac{1}{R} + a_4 \cdot D \right) \cdot C \quad (4)$$

where

const₂ equation constant for variable concentration of modifier,

C concentration of isopropanol (modifier) in the mobile phase (heptane) (%).

A comparison between the theoretical (t_{pred}) and the experimental results (t_{exp}), shows satisfactory agreement (Fig. 1).

Equation 4 contains two parts: the left part is independent on the concentration of modifier, and the right one that reflects its influence. Thus, with increasing concentrations of isopropanol the retention time of alkyl naphthyl ketones decrease; in the case when the experiment is conducted at constant concentration of modifier (C = const), Eq. 4 transforms into Eq. 3, and gives retention times if pure heptane is used as a mobile phase. As shown in Tables 5 and 6, the relative error in prediction through Eq. 4 does not exceed 8%.

To confirm or reject the assumptions that were drawn based on the QSAR model we performed DFT and MP2 calculations on the complexes of α- and β-alkyl naphthyl ketones with Ag⁺ and AgOCH₃. While the choice of Ag⁺ is straightforward, the use of AgOCH₃ is determined by the assumption that under the experimental chromatographic

Table 4 Correlation coefficients (Eq. 3), experimental (t_{exp} , min) and computed (t_{pred} , min) retention times and relative error of prediction (δ ,%) for constant concentration (C) at four temperatures ($T_1=293.15$ K, $T_2=303.15$ K, $T_3=313.15$ K, $T_4=323.15$ K) based on MP2 descriptors

Coefficient	T ₁			T ₂			T ₃			T ₄		
	C=0.045											
const	-141.477			-156.268			-168.913			-176.901		
a ₁	45.068			50.107			54.021			55.714		
a ₂	38.026			42.274			46.053			48.593		
r	0.992579			0.990967			0.990428			0.991670		
r ²	0.985213			0.982015			0.980947			0.983409		
C=0.06												
const	-91.8455			-101.835			-115.757			-125.612		
a ₁	29.5932			33.666			37.855			40.427		
a ₂	24.6644			27.573			31.511			34.465		
r	0.995028			0.992811			0.991921			0.991275		
r ²	0.990081			0.985675			0.983908			0.982626		
C=0.075												
const	-34.0121			-41.4354			-47.4567			-57.8805		
a ₁	11.2351			14.7730			16.7738			19.6364		
a ₂	9.5631			11.3922			13.0807			15.8694		
r	0.995537			0.997493			0.995945			0.995710		
r ²	0.991094			0.994992			0.991906			0.991439		
Compound	t_{exp}	t_{pred}	δ	t_{exp}	t_{pred}	δ	t_{exp}	t_{pred}	δ	t_{exp}	t_{pred}	δ
C=0.045												
β -C ₃ H ₇ -	28.56	28.03	1.86	33.06	32.18	2.66	37.18	36.19	2.66	40.19	39.09	2.74
α -C ₇ H ₁₅ -	19.01	19.18	0.89	22.04	22.33	1.32	25.27	25.57	1.19	27.78	28.13	1.26
C=0.06												
β -C ₃ H ₇ -	18.55	18.22	1.78	21.93	21.41	2.37	25.45	24.88	2.24	28.61	27.88	2.55
α -C ₇ H ₁₅ -	12.28	12.41	1.06	14.63	14.79	1.09	17.27	17.44	0.98	19.67	19.93	1.32
C=0.075												
β -C ₃ H ₇ -	8.74	8.58	1.83	9.87	9.77	1.01	11.46	11.28	1.57	13.37	13.14	1.72
α -C ₇ H ₁₅ -	6.32	6.38	0.95	6.81	6.87	0.88	7.89	7.99	1.27	9.19	9.28	0.98

Table 5 Correlation coefficients (Eq. 4), experimental (t_{exp} , min) and computed (t_{pred} , min) retention times and relative error of prediction (δ ,%) for variable concentration (C) at four temperatures ($T_1=293.15$ K, $T_2=303.15$ K, $T_3=313.15$ K, $T_4=323.15$ K) based on DFT descriptors

Coefficient	T ₁			T ₂			T ₃			T ₄		
	const	-11.761			-13.845			-11.14			-11.88	
a ₁	80.088			85.770			95.38			93.86		
a ₂	-934.785			-968.750			-1064.31			-1007.09		
a ₃	11.523			14.073			14.53			16.27		
a ₄	-88.316			-113.150			-126.62			-143.01		
r	0.9965			0.9967			0.9955			0.9949		
r ²	0.9930			0.9935			0.9911			0.9898		
Compound	t_{exp}	t_{pred}	δ	t_{exp}	t_{pred}	δ	t_{exp}	t_{pred}	δ	t_{exp}	t_{pred}	δ
C=0.045												
β -C ₃ H ₇ -	28.56	27.61	3.33	33.06	31.97	3.3	37.18	35.90	6.13	40.19	39.07	2.79
α -C ₇ H ₁₅ -	19.01	18.86	0.78	22.04	22.15	0.5	25.27	25.10	0.67	27.78	27.86	0.29
C=0.06												
β -C ₃ H ₇ -	18.55	18.25	1.62	21.93	21.13	3.65	25.45	23.87	6.21	28.61	26.45	7.55
α -C ₇ H ₁₅ -	12.28	12.44	1.3	14.63	14.41	1.5	17.27	16.48	4.57	19.67	18.54	5.74
C=0.075												
β -C ₃ H ₇ -	8.74	8.90	1.83	9.87	10.29	4.25	11.46	11.83	3.23	13.37	13.83	3.44
α -C ₇ H ₁₅ -	6.32	6.01	4.91	6.81	6.67	2.06	7.89	7.86	0.38	9.19	9.23	0.44

Table 6 Correlation coefficients (Eq. 4), experimental (t_{exp} , min) and computed (t_{pred} , min) retention times and relative error of prediction (δ ,%) for variable concentration (C) at four temperatures ($T_1=293.15\text{K}$, $T_2=303.15\text{K}$, $T_3=313.15\text{K}$, $T_4=323.15\text{K}$) based on MP2 descriptors

Coefficient	T_1			T_2			T_3			T_4		
const	-89.160			-99.897			-110.76			-120.18		
a_1	85.837			92.336			98.88			99.16		
a_2	28.464			32.693			36.77			40.23		
a_3	-953.395			-991.440			-1044.45			-1009.43		
a_4	-72.784			-93.353			-109.06			-120.62		
r	0.996970			0.996772			0.995915			0.994849		
r^2	0.993949			0.993555			0.991846			0.989726		
Compound	t_{exp}	t_{pred}	δ	t_{exp}	t_{pred}	δ	t_{exp}	t_{pred}	δ	t_{exp}	t_{pred}	δ
C=0.045												
β -C ₃ H ₇ -	28.56	27.50	3.71	33.06	31.78	3.87	37.18	36.00	4.34	40.19	39.11	2.69
α -C ₇ H ₁₅ -	19.01	19.12	0.58	22.04	22.47	1.95	25.27	25.87	2.37	27.78	28.61	2.99
C=0.06												
β -C ₃ H ₇ -	18.55	18.30	1.35	21.93	21.14	3.60	25.45	24.14	5.26	28.61	26.72	6.6
α -C ₇ H ₁₅ -	12.28	12.65	3.01	14.63	14.67	0.27	17.27	17.00	1.56	19.67	19.11	2.85
C=0.075												
β -C ₃ H ₇ -	8.74	9.10	4.12	9.87	10.50	6.38	11.46	12.28	7.16	13.37	14.33	7.18
α -C ₇ H ₁₅ -	6.32	6.18	2.22	6.81	6.86	0.73	7.89	8.13	3.04	9.19	9.61	4.57

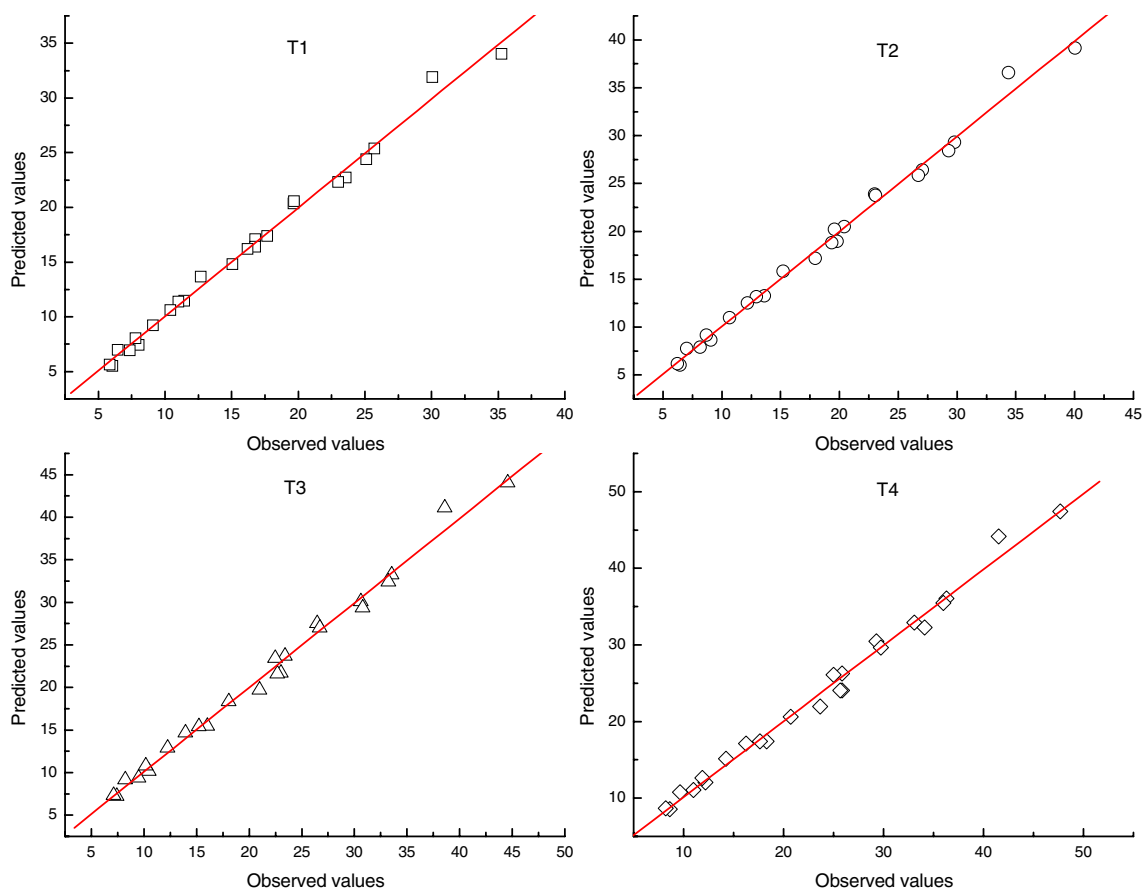
**Fig. 1** Experimental (t_{exp}) vs. predicted (t_{pred}) through the Eq. 4 retention times of alkylnaphthyl ketones at four different temperatures (T_1 , T_2 , T_3 , T_4)

Table 7 Computed complexation energy and relative stability of complexes of 1- and 2-methylnaphthyl ketones with Ag⁺ and AgOCH₃ at the different levels of theory

Ketones	Ag ⁺						AgOCH ₃	
	B3LYP/LANL2DZ		B3PW91/DZVP		MP2/DZVP		B3LYP/LANL2DZ	
	ΔE ^a , kcal/mol	ΔΔE ^b , kcal/mol	ΔE, kcal/mol	ΔΔE, kcal/mol	ΔE, kcal/mol	ΔΔE, kcal/mol	ΔE, kcal/mol	ΔΔE, kcal/mol
1,2-α-Me (1)	-51.1	6.4	-44.5	5.3	-42.4	4.9	-21.4	0.0
3,4-α-Me (2)	-	-	-	-	-	-	-13.3	8.1
5,6-α-Me (3)	-42.2	15.3	-32.3	17.5	-	-	-17.1	4.3
7,8-α-Me (4)	-57.5	0.0	-49.8	0.0	-47.0	0.0	-17.9	3.5
1,2-β-Me (5)	-48.0	0.0	-41.4	0.0	-39.5	0.0	-21.1	0.0
3,4-β-Me (6)	-36.4	11.7	-31.3	10.1	-	-	-14.0	7.1
5,6-β-Me (7)	-37.3	10.8	-32.0	9.3	-	-	-14.1	7.0
7,8-β-Me (8)	-38.1	10.0	-32.7	8.7	-31.4	8.1	-13.8	7.3

ΔE^a – complexation energy as described in Methods section; ΔΔE^b – is the difference between the respective complexes relative to the most stable one

conditions silver is likely covalently bonded to the stationary phase. Such an approach was found to be valid for the example of methylbenzenes and methylnaphthalenes complexation with silver(I) [29, 30].

Formation of complexes was found (Table 7) to be exothermic ranging from ca -31 to -51 kcal mol⁻¹ (for Ag⁺) and in the range of -14 ... -21 kcal mol⁻¹ (for AgOCH₃). Much higher exothermicity in the case of Ag⁺ relative to AgOCH₃ can be accounted for by an ionic nature of complexes.

While the DFT computations allow to locate both types of complexes (Scheme 3), *i.e.* *via* the aromatic ring and *via* the carbonyl oxygen, MP2 displays formation only the complex *via* carbonyl oxygen, nevertheless, demonstrating the similar trends in changes of energies and geometrics. The energy gap between the two most stable complexes in the case of α-

methylnaphthyl ketones is ca 3.5 – 6 kcal mol⁻¹ and in the case of β-methylnaphthyl 7 – 10 kcal mol⁻¹ (Table 7). The same behaviour was also found for ethyl- and propylketones (not shown). Optimized geometries of the most stable complexes with Ag⁺ and the complex with AgOCH₃ are depicted in Figure 2.

The distant orientation (Fig. 2) of the alkyl groups relative to Ag(I) agrees well with our QSRR model.

Conclusions

Based on the experimentally obtained retention times of arylalkyl ketones the QSRR-model for constant and variable concentration of modifier (isopropanol) is developed. The retention times of alkylnaphthyl ketones on

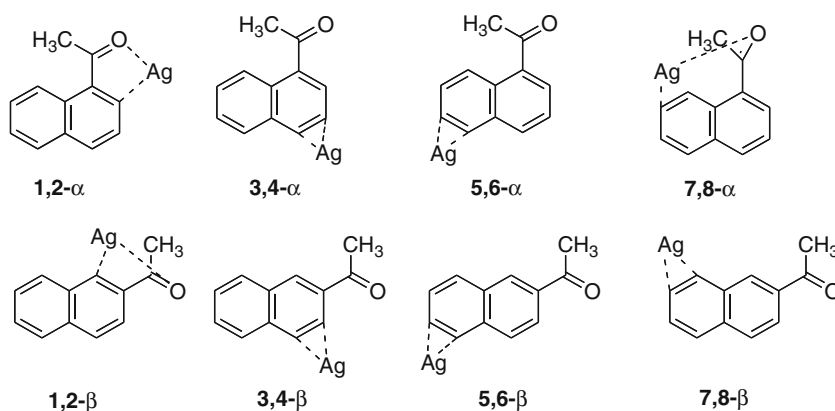
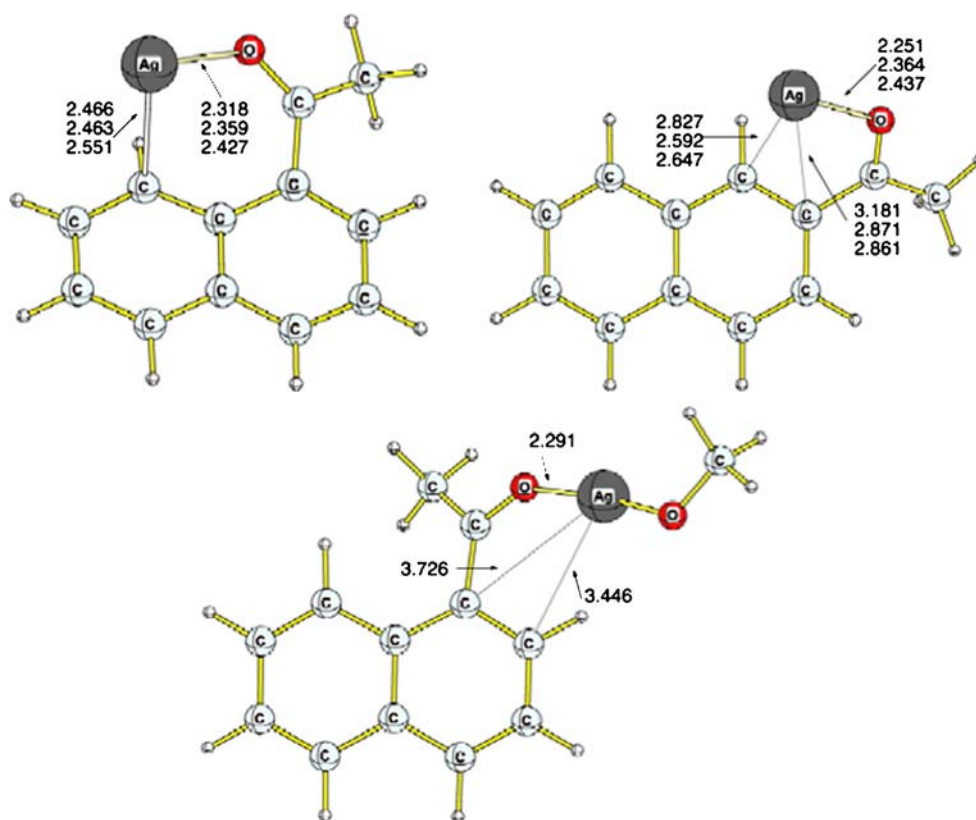
Scheme 3 Schematic representation of various types of complexes

Fig. 2 Optimized geometries of the most stable complexes with Ag^+ and AgOCH_3 {bond lengths in Å, B3LYP/LANL2DZ – first entry, B3PW91/DZVP – second entry, MP2/DZVP – third entry}



silver-containing stationary phase are influenced by dipole moment, length of the alkyl substituent as well as by the concentration of the modifier in the mobile phase.

The B3PW91/DZVP and MP2/DZVP computations favour formation of Ag(I) complexes *via* the carbonyl oxygen and agree well with each other. Despite the fact that MP2 describes the weak interaction better than DFT, this less expensive method is still valid for the QSRR modelling. From the QSRR/DFT/MP2 studies we can assume that the interactions of alkylnaphthyl ketones with silver-containing stationary phases proceed *via* the complexation through the oxygen atom of the carbonyl group both with and without modifier.

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