

# Kinetics and thermochemistry of the unusual $[2\pi + 2\sigma + 2\sigma]$ -cycloaddition of quadricyclane with some dienophiles

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## Abstract

Kinetic parameters of the unusual  $[2\pi + 2\sigma + 2\sigma]$ -cycloaddition reactions of quadricyclane (**1**) with tetracyanoethylene (**2**), 4-phenyl-1,2,4-triazoline-3,5-dione (**3**), *N*-phenylmaleimide (**4**), and diethyl azodicarboxylate (**5**) are determined experimentally. Additionally, the enthalpies of **1** + **2** reaction in 1,4-dioxane solution ( $-236.6 \pm 1.0$  kJ mol<sup>-1</sup>) and **1** + **3** reaction in toluene ( $-255.0 \pm 2.8$  kJ mol<sup>-1</sup>) are determined calorimetrically and shown to be the largest in absolute magnitude among all known cycloaddition reactions involving these dienophiles. Solvent effect on the rate of **1** + **3** reaction in 11 solvents is studied and found to be moderate and similar to that of the conventional Diels-Alder and ene reactions. The difference in the reaction rate constants of **1** with different dienophiles can be up to 9 orders of magnitude and is mainly caused by the difference in activation enthalpies. This difference is not correlated with the standard enthalpies of reactions and is likely the result of high sensitivity of the  $[2\pi + 2\sigma + 2\sigma]$  reaction rates to the energy of donor-acceptor interactions between the reactants.

## KEYWORDS

$[2\pi + 2\sigma + 2\sigma]$  reaction, 4-phenyl-1,2,4-triazoline-3,5-dione, quadricyclane, rate constants, reaction heat, tetracyanoethylene

## 1 | INTRODUCTION

The unusual combination of the quadricyclane (tetracyclo[3.2.0.0<sup>2,7</sup>.0<sup>4,6</sup>]heptane) (**1**) high strain energy, which equals 328 kJ mol<sup>-1</sup>,<sup>[1]</sup> and its high thermal stability<sup>[2]</sup> has attracted the attention of researchers. Quadricyclane can be readily prepared by irradiation of norbornadiene (bicyclo[2.2.1]hepta-2,5-diene).<sup>[3]</sup> The reverse symmetry-forbidden reaction accompanied by the release of the captured energy (88 kJ mol<sup>-1</sup>) occurs upon heating or in the presence of a catalyst. Thus, the quadricyclane-norbornadiene pair and their substituted derivatives are promising for the solar energy accumulation and storage systems.<sup>[4]</sup> Transition metals are the most effective catalysts for these isomerization

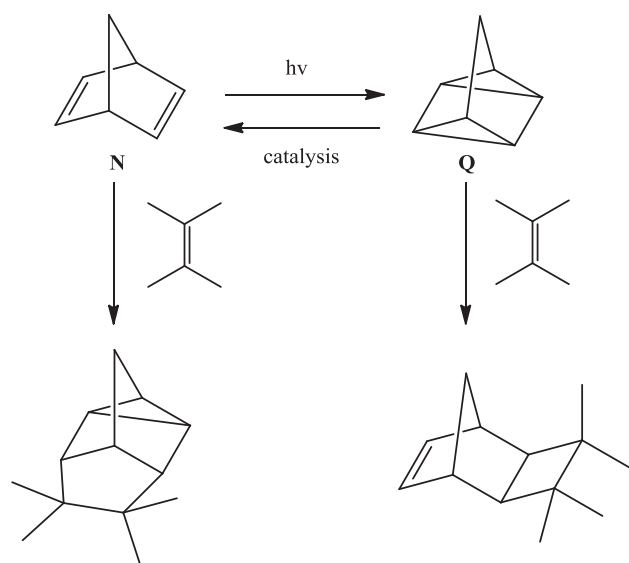
processes; for example, rhodium complexes can cause the rate acceleration by 19 orders of magnitude.<sup>[5]</sup>

The most peculiar feature of quadricyclanes is their ability to participate in  $[2\pi + 2\sigma + 2\sigma]$ -cycloaddition reactions, which are to some extent similar to  $[2\pi + 2\sigma]$ -cycloadditions of dienophiles with the strained cyclopropane ring systems (bicyclo[2.1.0]pentane<sup>[6]</sup> and bicyclobutane<sup>[7]</sup>). Quadricyclanes can form adducts with various activated dienophiles containing C=C, C≡C, C=O, C=S, C=Si, C=N, and N=N bonds.<sup>[8]</sup> In most cases, the process is stereoselective and leads to exo-adducts formation. The synthetic potential of such cycloadditions is still to be explored. Recently, **1** has been used as a starting point in the total synthesis of a potent antifungal agent—hippolachnin A.<sup>[9]</sup> The

parent molecule of norbornadiene reacts with electrophilic olefins via the different,  $[2\pi + 2\pi + 2\pi]$  (homo Diels-Alder)-cycloaddition mechanism with much smaller reaction rates (Scheme 1).<sup>[8,10–12]</sup> The adducts of the same structure can be obtained from quadricyclane in the presence of transition metal complexes, which catalyze its isomerization into norbornadiene.

The comparison of the physical properties of **1** with those of several isomeric cyclic hydrocarbons is given in Table 1. **1** has a low ionization potential and a very large enthalpy of formation in comparison with its isomers, which can also be explained by its high strain energy. The low ionization potential of **1** facilitates the formation of adducts with strong  $\pi$ -acceptors in cycloaddition reactions.<sup>[8]</sup>

In numerous syntheses reported in the literature, the adducts of quadricyclanes with many different dienophiles



**SCHEME 1** Structures of norbornadiene (**N**), quadricyclane (**Q**), and their  $[2\pi + 2\pi + 2\pi]$ -cycloadducts of **N** and  $[2\pi + 2\sigma + 2\sigma]$ -cycloadducts of **Q** with dienophiles

were reported.<sup>[8]</sup> However, the quantitative data on the physicochemical parameters of  $[2\pi + 2\sigma + 2\sigma]$ -cycloaddition reactions are extremely scarce. Another important aspect to be studied is the solvent effect on the kinetics and selectivity of these reactions.

In the present work, we determine kinetic and thermochemical parameters for the reaction of **1** with several dienophiles at different temperatures and pressures and in various solvent media. One of the considered dienophiles, tetracyanoethylene (**2**), has the strong  $\pi$ -accepting ability (electron affinity = 2.88 eV).<sup>[14]</sup> It is the most active dienophile in the Diels-Alder  $[4\pi + 2\pi]$ -cycloaddition reactions with electron-donor dienes.<sup>[15]</sup> Recently, we have reported the values of the rate constants and enthalpies<sup>[16]</sup> of the reaction of **1** with **2**. The heat effect of this reaction exceeds all the known values for the reactions of 1,3-dienes with **2**, and the rate constant is also very high, which is obviously linked with the high strain energy of **1**. Another dienophile, 4-phenyl-1,2,4-triazoline-3,5-dione (**3**), exhibits moderate  $\pi$ -acceptor properties, close to those of maleic anhydride (0.97 eV) and *N*-phenylmaleimide (0.89 eV).<sup>[15,17]</sup> However, the rate constant of some Diels-Alder reactions with **3** is by 5–6 orders of magnitude higher than those with the latter compounds. In many Diels-Alder reactions, **3** is even more active<sup>[15,17–19]</sup> than **2**. Only in the reaction with a strong  $\pi$ -donor diene, 9,10-dimethylanthracene (ionization potential = 7.08 eV), **2** reacts faster<sup>[19,20]</sup> than **3**. The reason for the higher activity of **3** may be an increased electrophilicity of N atoms in N=N bonds in comparison with C atoms in C=C bonds and a relatively low bond energy of the N=N bonds.<sup>[18]</sup> **3** also shows a high activity in the ene reactions with alkenes involving the migration of allylic hydrogen and the shift of C=C double bond.<sup>[18]</sup> When such a shift is not possible, other skeletal rearrangements and  $[2\pi + 2\pi]$ -cycloaddition reactions can take place. A structural analog of **3** with C=C bond, *N*-phenylmaleimide (**4**), is moderately active in the Diels-Alder

**TABLE 1** Physical properties of isomeric C<sub>7</sub>H<sub>8</sub> cyclic hydrocarbons at 25°C<sup>[1,8,13]</sup>

Parameters	Quadricyclane	Norbornadiene	Cycloheptatriene	Toluene
$d$ , g cm <sup>-3</sup>	0.9796	0.906	0.9105	0.8669
$V_m$ , cm <sup>3</sup> mol <sup>-1</sup>	94.1	101.7	101.2	106.3
$\Delta_{\text{vap}}H$ , kJ mol <sup>-1</sup>	37.0	33.6	38.7	38.0
Bp, K	381	362	389	384
Mp, K	229	254	195	178
$n_D$	1.483	1.470	1.5208	1.4969
$MR$ , cm <sup>3</sup> mol <sup>-1</sup>	35.1	37.3	40.1	40.7
$\Delta_f H$ , kJ mol <sup>-1</sup>				
gas	339.1	247.6	183.7	50.1
liquid	302.1	214	145.0	12.0
Ionization potential, eV	7.40	8.69	—	8.82

reactions and not prone to participate in other types of pericyclic reactions. The last-mentioned of the considered dienophiles, diethyl azodicarboxylate (**5**), has a low activity in the Diels-Alder reactions and preferably participates in ene reactions.<sup>[18]</sup>  $[2\pi + 2\sigma + 2\sigma]$  reactions of **1** with **2-5** lead to the selective formation of exo-adducts **6-9** (Scheme 2).<sup>[8,21]</sup>

The data for  $[2\pi + 2\sigma + 2\sigma]$ -cycloaddition reactions of **1** obtained in the present work are compared with the previously reported physicochemical parameters for the cycloadditions of its isomers, norbornadiene and cycloheptatriene, and several 1,3-dienes with the same dienophiles.

## 2 | EXPERIMENTAL SECTION

### 2.1 | Materials

**1** was synthesized from norbornadiene using a known procedure,<sup>[3]</sup> dried with metallic sodium, and distilled twice under reduced pressure (600 Pa). The residual concentration of norbornadiene and other impurities in **1** was determined by the titration of a red solution of **2** in toluene with the solution of **1**. Since the rate constant of the reaction of norbornadiene<sup>[18]</sup> with **2** ( $1.3 \cdot 10^{-5} \text{ L mol}^{-1} \text{ s}^{-1}$ ) is by 7 orders of magnitude lower than that of the reaction  $\mathbf{1} + \mathbf{2} \rightarrow \mathbf{6}$  ( $104.4 \text{ L mol}^{-1} \text{ s}^{-1}$ ),<sup>[16]</sup> the amount of norbornadiene that reacted with **2** at the equivalence point is negligibly small, while **1** converts into cycloadduct **6** very fast and completely. The titration showed that the purity of **1** is equal to  $97\% \pm 0.5\%$ . Tetracyanoethylene **2** and 4-phenyl-triazoline-3,5-dione **3** (Aldrich, 97%) were purified by sublimation ( $100^\circ\text{C}$ , 100 Pa); melting point of **2** is  $200^\circ\text{C}$  to  $201^\circ\text{C}$  (lit  $201^\circ\text{C}$ ),<sup>[22]</sup> and melting point of **3** is  $165^\circ\text{C}$  to  $170^\circ\text{C}$  with decomposition (lit  $165^\circ\text{C}$ - $170^\circ\text{C}$ , decomp).<sup>[23]</sup> The purity of **3** was checked by comparison of the molar

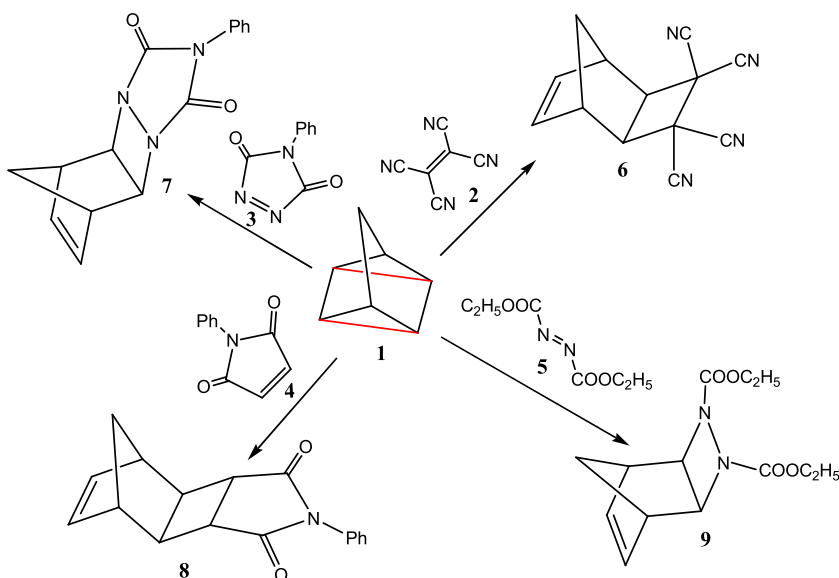
absorptivities in UV-Vis spectra with the literature data.<sup>[17,24,25]</sup> The melting points and nuclear magnetic resonance spectra of obtained adducts **6-9** also coincide with the previously described.<sup>[8,13,21,26]</sup> All the solvents were purchased from commercial suppliers and purified by known methods.<sup>[27]</sup>

### 2.2 | Kinetic measurements at atmospheric pressure

For kinetic measurements, an UV-Vis spectrophotometer (Hitachi-2900, Japan) was used. Its stock cell holder (type 210-2111) was removed and replaced with a custom-made brass cell holder having an internal circulation of thermostated water to improve the temperature stability and control. In the experiments, quartz spectrophotometer cells ( $L \times W \times H = 1 \times 1 \times 4 \text{ cm}$ ) were filled with the reactants solution, sealed with a ground stopper, and inserted into the holder pocket having all the walls abutting the walls of the holder tightly. The holes in the opposite walls of the holder allow the light beam to pass through the cell. The temperature inside the cell is stable within  $\pm 0.1^\circ\text{C}$ . The rate of fast reaction  $\mathbf{1} + \mathbf{2} \rightarrow \mathbf{6}$  was measured using the stopped-flow method (Cary 50 Bio spectrophotometer with RX 2000 rapid mixing accessory).

All the reaction rates were followed by the change in the absorbance of dienophiles **2-5** near their absorption maxima. The initial concentrations of dienophiles were 15 to 100 times lower than those of **1**. Slow reactions  $\mathbf{1} + \mathbf{4} \rightarrow \mathbf{8}$  and  $\mathbf{1} + \mathbf{5} \rightarrow \mathbf{9}$  were studied in neat liquid **1**. Quadricyclane **1** and adducts **6-9** are transparent at measurement wavelengths.

Chemical stability of dienophiles **2** and **3** in various solvents was checked before the kinetic measurements. It has



**SCHEME 2** Reagents and products of the studied  $[2\pi + 2\sigma + 2\sigma]$ -cycloaddition reactions

been found that **3** reacts very quickly with dimethyl sulfoxide, and this system was excluded from consideration. The absorption of **3** in dimethylformamide has changed for about 7% during the reaction time, which was taken into account in the rate constants calculation. Compound **5** undergoes slow decomposition even at moderate temperatures. However, the half-life time of **5** in benzene solution at 35°C is about 250 days, which is 450 times greater than that in the experimental conditions in the reaction with **1**.

The relative standard errors for the values of the rate constants were no more than 3%, and the standard errors for the enthalpies and entropies of activation derived using Eyring equation were not more than 2 kJ mol<sup>-1</sup> and 6 J mol<sup>-1</sup> K<sup>-1</sup>, respectively.

### 2.3 | Kinetic measurements at elevated pressure

The rates of reactions under elevated pressure were measured at 25°C using a high pressure system consisting of a high pressure pump (HP-500, Japan), a high pressure optical cell (PCI-500, Japan), and an UV-Vis spectrophotometer (SCINCO, Korea). The activation volume ( $\Delta V_{\text{exp}}^{\ddagger}$ ) of reaction **1** + **3** → **7** in toluene was calculated from the pressure dependence of the reaction rate at the constant temperature. The pressure derivative of the rate

constant logarithm at the standard 1 bar pressure is proportional to the activation volume:

$$\left[\frac{\partial \ln k_p}{\partial p}\right]_{p=1 \text{ bar}} = -\Delta V_{\text{exp}}^{\ddagger}/RT \quad (1)$$

To evaluate this derivative, one can fit the dependence of the experimental rate constants on the pressure using the following equation:

$$\ln(k_p/k_{p=1 \text{ bar}}) = C \ln[(B + P)/B] \quad (2)$$

Here,  $C$  and  $B$  are empirical constants. Another possibility is to measure the rate constant at 1000 bar pressure and to use the previously reported<sup>[28]</sup> linear correlation with the secant modulus  $\ln(k_{p=1000 \text{ bar}}/k_{p=1 \text{ bar}})$ :

$$\left[\frac{\partial \ln k_p}{\partial p}\right]_{p=1 \text{ bar}} = (1.15 \pm 0.03) \ln(k_{p=1000 \text{ bar}}/k_{p=1 \text{ bar}})/1000 \quad (3)$$

The values of the corrected activation volumes  $\Delta V_{\text{corr}}^{\ddagger}$  were obtained regarding the solvent compression.<sup>[29]</sup>

$$\Delta V_{\text{corr}}^{\ddagger} = V_{\text{exp}}^{\ddagger} + \beta_T RT \quad (4)$$

Here,  $\beta_T$  is the isothermal compressibility of the solvent.

Measurements for reaction **1** + **2** → **6** could not be conducted at high pressure because of its very high rate. At the same time, reactions **1** + **4** → **8** and **1** + **5** → **9**

**TABLE 2** Rate constants ( $k_2$ , L mol<sup>-1</sup> s<sup>-1</sup>), enthalpies ( $\Delta H^{\ddagger}$ , kJ mol<sup>-1</sup>), entropies ( $\Delta S^{\ddagger}$ , J mol<sup>-1</sup> K<sup>-1</sup>), and the Gibbs free energies activation ( $\Delta G^{\ddagger}$ , kJ mol<sup>-1</sup>, 25°C) for the studied reactions in various solvents

Reaction/Solvent	$\epsilon^a$	$k_2$ (15°C)	$k_2$ (25°C)	$k_2$ (35°C)	$\Delta H^{\ddagger}$	$-\Delta S^{\ddagger}$	$\Delta G^{\ddagger}$
<b>1 + 3 → 7</b>							
Tetrahydrofuran	7.4	0.018	0.038	0.079	51.3	100	81.1
Ethyl acetate	6.0	0.034	0.068	0.130	47.6	108	79.8
1,4-Dioxane	2.2	0.047	0.091	0.179	46.4	109	79.0
Toluene	2.3	0.145	0.282	0.444	39.6	123	76.3
Acetonitrile	37.5	0.526	0.916	1.595	38.5	117	73.2
Benzene	2.3	0.241	0.417	0.691	36.5	130	75.2
Tetrachloromethane	2.2	0.373	0.625	1.025	34.8	132	74.2
Chlorobenzene	5.6	0.607	0.99	1.550	32.4	136	73.0
1,2-Dichloroethane	10.3	2.37	3.61	5.51	28.6	138	69.8
Trichloromethane	4.6	4.38	6.08	7.43	21.1	159	68.5
Dimethylformamide	36.7	0.068	0.162	0.340	55.4	75	77.8
<b>1 + 2 → 6</b>							
Toluene	2.3	—	104.4 <sup>b</sup>	178.8 <sup>c</sup>	18.0	145	61.2
<b>1 + 4 → 8</b>							
Neat <b>1</b>	2.2	1.47·10 <sup>-7</sup>	3.38·10 <sup>-7</sup>	8.63·10 <sup>-7</sup>	71.7	143	116
<b>1 + 5 → 9</b>							
Neat <b>1</b>	2.2	1.24·10 <sup>-6</sup>	2.80·10 <sup>-6</sup>	6.49·10 <sup>-6</sup>	67.1	140	109

<sup>a</sup>The values of the relative permittivity of solvents are taken from previous study.<sup>[27]</sup>

<sup>b</sup>At 20°C.

<sup>c</sup>At 40°C.

were either not studied at elevated pressures because of their too low rates.

## 2.4 | Volumetric measurements

The values of activation volumes were compared with the standard molar reaction volumes  $\Delta V_{r-n}$ . The values of  $\Delta V_{r-n}$  were calculated as the difference between the partial molar volumes of adduct and reactants in solution. The values of the partial molar volumes of **1**, **3**, and **7** were calculated from the densities of their dilute solutions at 25°C measured using DSA-5000M densitometer according to the equation

$$V = 1000 \cdot \frac{d_0 - d_1}{m d_1 d_0} + \frac{M}{d_1} \quad (5)$$

where  $d_0$  and  $d_1$  are the densities of pure solvent and solution, respectively,  $m$  is the solution molality (in mol kg<sup>-1</sup> solvent), and  $M$  is the solute molar mass.

## 2.5 | Calorimetric measurements

The enthalpies of reactions were determined at 25°C using a differential calorimeter as described previously.<sup>[18]</sup> The samples of solid **2** or **3** (25–35 mg) were put into small stainless-steel tubes having an external thread on both sides. The tube ends were covered with thin (0.1 mm) Teflon rings and sealed with open top screw caps. These tubes were placed in the calorimetric cells containing solution of **1** (taken in excess). After the thermal equilibrium has been reached, the Teflon seals were cut with a blade, and the solid dienophile dissolved and reacted with **1**. The enthalpies of the dienophiles dissolution ( $4.3 \pm 0.2$  kJ mol<sup>-1</sup> for solid **2** in 1,4-dioxane<sup>[30]</sup> and  $18.3 \pm 0.5$  kJ mol<sup>-1</sup> for solid **3** in toluene<sup>[17]</sup>) were subtracted from the observed heat effects to obtain the standard molar enthalpies of cycloaddition reactions in solution.

## 3 | RESULTS AND DISCUSSION

### 3.1 | Rate constants of [2π + 2σ + 2σ]-cycloaddition

The rate constants and activation parameters of reaction **1** + **3** → **7** were measured in 11 solvents and are given in Table 2. The rate constants of a fast reaction **1** + **2** → **6** in toluene averaged over 10 repeated stopped-flow measurements, and the rate constants of slow reactions **1** + **4** → **8** and **1** + **5** → **9** studied in neat quadricyclane are also given in this table.

Despite dienophile **3** usually exhibiting markedly increased activity in comparison with **2** in [4π + 2π]-cycloaddition reactions,<sup>[17–19]</sup> reaction **1** + **2** → **6** goes almost 400

times faster than reaction **1** + **3** → **7**. Another surprising result is that the cycloaddition of **1** to **3** goes  $8.3 \cdot 10^5$  faster than **1** to **4** and  $10^5$  times faster than **1** to **5** in the media with almost the same polarity. The cycloaddition rates in polar aprotic solvents, acetonitrile and dimethylformamide, are comparable with those in low polar solvents and are significantly lower than in C–H acidic solvents (1,2-dichloroethane

**TABLE 3** Rate constants ( $k_2$ , L mol<sup>-1</sup> s<sup>-1</sup>) and enthalpies ( $\Delta H_{r-n}$ , kJ mol<sup>-1</sup>) of some [2π + 2σ + 2σ]-, [4π + 2π]-, and [2π + 2π + 2π]-cycloaddition reactions with dienophiles **2–5** at 25°C

Reaction	$k_2$	$-\Delta H_{r-n}$
[2π + 2σ + 2σ]		
Quadricyclane + <b>2</b>	120, S1	236.5, S2
Quadricyclane + <b>3</b>	0.282, S1	255.1, S1
Quadricyclane + <b>4</b>	$3.7 \cdot 10^{-7}$ , S3	—
Quadricyclane + <b>5</b>	$2.8 \cdot 10^{-6}$ , S3	—
[4π + 2π]		
9,10-dimethyl anthracene + <b>2</b>	2810 <sup>a</sup> , S1	88 <sup>a</sup> , S2
9,10-dimethyl anthracene + <b>3</b>	12200 <sup>b</sup> , S1	118 <sup>b</sup> , S1
9,10-dimethyl anthracene + <b>4</b>	0.030 <sup>c</sup> , S2	117 <sup>c</sup> , S2
9,10-dimethyl anthracene + <b>5</b>	$1.57 \cdot 10^{-3d}$ , S4	—
[4π + 2π]		
Cyclopentadiene + <b>2</b>	478 <sup>e</sup> , S2	113 <sup>c</sup> , S2
Cyclopentadiene + <b>3</b>	160 000 <sup>d</sup> , S1	134 <sup>d</sup> , S1
Cyclopentadiene + <b>4</b>	0.087 <sup>c</sup> , S2	142 <sup>c</sup> , S2
Cyclopentadiene + <b>5</b>	0.0322 <sup>d</sup> , S4	112 <sup>d</sup> , S4
[4π + 2π]		
Cyclohexadiene + <b>2</b>	0.0492 <sup>f</sup> , S1; 1.37 <sup>e</sup> , S5	130 <sup>f</sup> , S1
Cyclohexadiene + <b>3</b>	6100 <sup>f</sup> , S1	140 <sup>f</sup> , S1
[4π + 2π]		
Cycloheptadiene + <b>2</b>	$1.73 \cdot 10^{-4f}$ , S1; $4.32 \cdot 10^{-3e}$ , S5	—
Cycloheptadiene + <b>3</b>	186 <sup>f</sup> , S1	140 <sup>f</sup> , S1
[4π + 2π]		
Cycloheptatriene + <b>2</b>	$3.6810^{-3f}$ , S1	90 <sup>f</sup> , S4
Cycloheptatriene + <b>3</b>	7.57 <sup>f</sup> , S1	110 <sup>f</sup> , S1
[2π + 2π + 2π]		
Norbornadiene + <b>2</b>	$1.3 \cdot 10^{-5g}$ , S1	—
Norbornadiene + <b>3</b>	$3.95 \cdot 10^{-3b}$ , S1	218 <sup>b</sup> , S1

<sup>a</sup>From Kiselev et al.<sup>[20]</sup>

<sup>b</sup>From Kiselev et al.<sup>[19]</sup>

<sup>c</sup>From Kiselev et al.<sup>[15]</sup>

<sup>d</sup>From Kiselev et al.<sup>[17]</sup>

<sup>e</sup>From Rücker et al.<sup>[22]</sup>

<sup>f</sup>From Kiselev et al.<sup>[18]</sup>

<sup>g</sup>From Brown et al.<sup>[31]</sup>

Solvents: S1—toluene; S2—1,4-dioxane; S3—quadricyclane; S4—1,2-dichloroethane; S5—dichloromethane.

and trichloromethane). In the studied systems, the enthalpies, not entropies of activation, are primarily responsible for the differences in the Gibbs free energies of activation and, consequently, in the values of the rate constants.

The values of activation entropy for the unusual  $[2\pi + 2\sigma + 2\sigma]$ -cycloaddition reactions are quite close to those for the conventional  $[4\pi + 2\pi]$  Diels-Alder reactions, while the enthalpies of activation for the latter are significantly lower. For example, in reaction of **2** with 9,10-dimethylanthracene in toluene at 25°C,  $\Delta S^\ddagger$  is equal to  $-138 \text{ J mol}^{-1} \text{ K}^{-1}$ ,<sup>[20]</sup> and with cycloheptatriene,  $\Delta S^\ddagger$  is  $-145 \text{ J mol}^{-1} \text{ K}^{-1}$ .<sup>[19]</sup>

### 3.2 | Enthalpies of $[2\pi + 2\sigma + 2\sigma]$ -cycloaddition

Highly exothermic reactions with a favorable balance of the energies of broken and newly formed bonds often, although not always,<sup>[15]</sup> have high rate constants. In the classic Diels-Alder  $[4\pi + 2\pi]$ -cycloaddition reactions, the standard enthalpies vary<sup>[19]</sup> from  $-50$  to  $-200 \text{ kJ mol}^{-1}$ . The measured standard enthalpies of  $[2\pi + 2\sigma + 2\sigma]$ -cycloaddition reactions are  $-236.6 \pm 1.1 \text{ kJ mol}^{-1}$  for reaction **1** + **2**  $\rightarrow$  **6** and  $-255.1 \pm 2.8 \text{ kJ mol}^{-1}$  for reaction **1** + **3**  $\rightarrow$  **7**. These reactions are accompanied by a record energy gain, exceeding all the known values for the Diels-Alder reactions of 1,3-dienes<sup>[15–19]</sup> with dienophiles **2** and **3**. This is obviously linked to a very high strain energy of the molecule of **1**. From the kinetical point of view, these 2 reactions are rapid ones. The rate of reaction **1** + **2**  $\rightarrow$  **6** is significantly higher than that for the reactions of **2** with isomeric cyclic hydrocarbons: norbornadiene and cycloheptatriene. (See Table 3 for a comparison of the enthalpies and the rate constants for cycloaddition reactions of **2-5** with various compounds.) However, similar values of the standard enthalpies are expected for very slow

reactions **1** + **4**  $\rightarrow$  **8** and **1** + **5**  $\rightarrow$  **9**. This means that the rate of  $[2\pi + 2\sigma + 2\sigma]$ -cycloaddition is determined not only by the large strain energy of reactant **1** but can be greatly reduced because of the unfavorable orbital interactions in the transition state.

### 3.3 | Standard activation and reaction volume

The activation volume  $\Delta V_{\text{exp}}^\ddagger$  was calculated by Equation 3 from the rate constants at 1 bar and 1000 bar pressures (0.282 and 0.745  $\text{L mol}^{-1} \text{ s}^{-1}$ , respectively). It equals  $-27.7 \pm 1.0 \text{ cm}^3 \text{ mol}^{-1}$ . Taking into account the toluene compressibility ( $92.1 \cdot 10^{-6} \text{ bar}^{-1}$ ),<sup>[32]</sup> the use of Equation 4 leads to the value of corrected activation volume  $-25.4 \pm 1.0 \text{ cm}^3 \text{ mol}^{-1}$ . The standard reaction volume was calculated as the difference between the measured partial molar volumes of the adduct ( $V_m(\mathbf{7}) = 199.7 \pm 1.0$ ) and the reactants ( $V_m(\mathbf{1}) = 93.7 \pm 0.1$  and  $V_m(\mathbf{3}) = 126.9 \pm 0.5 \text{ cm}^3 \text{ mol}^{-1}$ ) in toluene solution.  $\Delta V_{\text{r-n}}$  turned out to be equals  $-20.9 \pm 1.5 \text{ cm}^3 \text{ mol}^{-1}$ , which means that the molecular volume of the activated complex is less than that of adduct **7**.

### 3.4 | Solvent effect on the reaction rate

In Table 4, we compare the data on the reactivity of **3** in the reaction with **1** and in the other cycloaddition reactions in different solvents. Solvent effect on the  $[2\pi + 2\sigma + 2\sigma]$ -cycloaddition of **3** with **1**,  $[4\pi + 2\pi]$ -cycloaddition of **3** with anthracene, ene reactions of **3** with alkenes, and even on the  $[2\pi + 2\pi]$ -cycloaddition reaction of **3** with 2-chloroethyl vinyl ether is small. The rate constants for each pair of these reactions are intercorrelated to a greater or lesser extent, Equation 5a-f. There is also a correlation between the logarithms of the rate constants and the standard enthalpies of the dissolution of **3** in corresponding solvents.

**TABLE 4** The rate constants ( $k_2$ ,  $\text{L mol}^{-1} \text{ s}^{-1}$ ) of cycloaddition reactions of **3** with quadricyclane (**1**) at 25°C; 2-chloroethyl vinyl ether (**10**) at 25°C; 2-methyl-2-butene (**11**) at 10°C; anthracene (**12**) at 25°C; norbornene (**13**) at 40°C; 3-hexene (**14**) at 20°C; and the standard enthalpies of solution of **3** at 25°C ( $\Delta_{\text{soln}}H(\mathbf{3})$ ,  $\text{kJ mol}^{-1}$ ) in various solvents

Solvent	3 + 1	3 + 10 <sup>[33]</sup>	3 + 11 <sup>[34]</sup>	3 + 12 <sup>[17]</sup>	3 + 13 <sup>[35]</sup>	3 + 14 <sup>[36]</sup>	$\Delta_{\text{soln}}H(\mathbf{3})$ <sup>[17]</sup>
Tetrahydrofuran	0.0382	—	0.060	0.028	0.327	0.0032	6.7
Ethyl acetate	0.068	0.014	0.109	0.057	0.312	0.0046	9.0
1,4-Dioxane	0.091	—	0.150	0.094	—	—	8.8
Toluene	0.282	—	0.64	0.33	0.775	—	18.3
Acetonitrile	0.916	0.043	0.57	0.32	0.623	—	14.2
Benzene	0.417	0.27	1.26	0.52	—	0.0354	20.6
Chlorobenzene	0.99	—	2.56	1.01	—	—	21.8
1,2-Dichloroethane	3.613	0.12	4.9	1.55	—	0.144	21.9
Trichloromethane	6.08	0.18	14.3	5.09	3.05	—	24.4
Dichloromethane	—	0.13	8.1	—	—	—	—
Dimethylformamide	0.162	—	0.077	—	0.453	—	—

$$\ln k(\mathbf{3} + \mathbf{10}) = (0.5624 \pm 0.0589) \ln k(\mathbf{3} + \mathbf{1}) - (2.8565 \pm 0.1026); R^2 = 0.9785; \quad (5a)$$

$$\ln k(\mathbf{3} + \mathbf{11}) = (1.0072 \pm 0.1010) \ln k(\mathbf{3} + \mathbf{1}) + (0.5599 \pm 0.1872); R^2 = 0.9341; \quad (5b)$$

$$\ln k(\mathbf{3} + \mathbf{12}) = (0.9160 \pm 0.0893) \ln k(\mathbf{3} + \mathbf{1}) - (0.3068 \pm 0.1655); R^2 = 0.9376; \quad (5c)$$

$$\ln k(\mathbf{3} + \mathbf{13}) = (0.4235 \pm 0.0921) \ln k(\mathbf{3} + \mathbf{1}) - (6.8209 \pm 0.1966); R^2 = 0.8755; \quad (5d)$$

$$\ln k(\mathbf{3} + \mathbf{14}) = (0.8656 \pm 0.0762) \ln k(\mathbf{3} + \mathbf{1}) - (2.9016 \pm 0.1716); R^2 = 0.9847; \quad (5e)$$

$$\ln k(\mathbf{3} + \mathbf{1}) = (0.2355 \pm 0.0445) \Delta_{\text{soln}} H(\mathbf{3}) - (4.6453 \pm 0.7738); R^2 = 0.7996. \quad (5f)$$

## 4 | CONCLUSION

The difference in the rate constants of the  $[2\pi + 2\sigma + 2\sigma]$ -cycloaddition reaction of quadricyclane with different dienophiles can be up to 9 orders of magnitude and is mainly caused by the difference in the activation enthalpies, while the values of activation entropies are quite close. The solvent effect on the rate constant is found to be analogous to that on  $[4\pi + 2\pi]$ -cycloaddition and ene reactions.

A large difference in the rates of  $[2\pi + 2\sigma + 2\sigma]$ -cycloadditions is not correlated with the standard enthalpies of these reactions. The reaction of **1** with **3** is  $18.5 \text{ kJ mol}^{-1}$  more exothermic than that with **2**, but 400 times slower. This fact can be the result of the high sensitivity of the  $[2\pi + 2\sigma + 2\sigma]$  reaction rates to the energy of donor-acceptor interactions between the reactants. A similar effect is usually observed for the Diels-Alder reactions. For example, the reaction of 9,10-dimethylantracene with *N*-phenylmaleimide **4** is  $29 \text{ kJ mol}^{-1}$  more exothermic than with tetracyanoethylene **2**, while the rate of reaction with a strong  $\pi$ -acceptor **2** is 5 orders higher. We can conclude that a huge strain energy of quadricyclane and exothermicity of its  $[2\pi + 2\sigma + 2\sigma]$ -cycloaddition reactions is not the main factor governing the relative reactivity of **1** with different dienophiles.

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## CONFLICT OF INTEREST

The authors declare no competing financial interest.

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