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Petra Linnartz[a]; Christoph A. Schalley[a]
[a] Kekulé-Institut für Organische Chemie und Biochemie der Universität, Bonn, Germany

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Deslipping of Rotaxanes with Axle Center Pieces of Different Lengths

PETRA LINNARTZ and CHRISTOPH A. SCHALLEY*

Kekulé-Institut für Organische Chemie und Biochemie der Universität, Gerhard-Domagk-Str. 1, D-53121 Bonn, Germany

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A series of rotaxanes equipped with tetralactam wheels and di-*t*-butyl stopper groups, which differ only with respect to the length of the alkyl chain serving as the axle center piece, are examined with respect to their deslipping behavior at elevated temperatures. ^{1}H NMR experiments are used to follow the deslipping reactions kinetically, and it is found that the axle length does not have a significant influence on the rate of deslipping. In accordance with expectation, this result confirms that the rate-determining step of the reaction is the passage of the wheel over the stopper group. It also sheds new light on earlier results on rotaxanes bearing ester groups in the axle center piece. The deslipping reaction rate for these rotaxanes was extremely dependent on the choice of solvent and the orientation of the ester groups. The rotaxanes presented here do not contain functional groups in their center pieces and no such effects are observed. For these rotaxanes, the simple model of a thin thread inside a macrocycle mechanically trapped by bulky stopper groups is valid.

Keywords: Rotaxanes; Interlocked molecules; Deslippage; Reaction kinetics

INTRODUCTION

The common mental representation of a rotaxane [1,2] is that of a thin axle threaded through the cavity of a macrocycle, which is hindered from deslipping by two bulky stopper groups at the axle ends. Consequently, the wheel is trapped on the axle by a so-called mechanical bond. In addition, non-covalent bonding between axle and wheel may occur, which is often the case, when template effects [3,4] are used for the synthesis of the rotaxane.

When this simple model is used to predict the outcome of deslipping experiments [5–10] (Scheme 1) with rotaxanes bearing stoppers of intermediate sizes, one arrives at the conclusion that the passage of the thickest part of the axle through the macrocycle cavity is the rate-determining step [11]. Consequently, all other barriers that might exist when the wheel is traveling along the axle should be lower in energy and they should not play a role for the deslipping kinetics.

In a recent study [12], we found however that the orientation of an ester group incorporated in the rotaxane axle dramatically changes the deslipping rates (Scheme 2), although the ester group was definitively not the thickest part of the axle, neither was it located at the stopper periphery so that simple steric factors might have been operative. Furthermore, one of the rotaxanes showed a strong solvent effect, whereas the other did not. This result to some extent contradicts the model described above. Consequently, we decided to examine a series of rotaxanes with different axle lengths with respect to their deslipping behavior (Chart 1). A common feature to the whole series is that none of them bears any functional group within the alkyl chain connecting the two stopper groups; just the length of the thread is varied. Compared to the size of the stoppers, the axles of rotaxanes **1–10** may indeed be considered thin threads. Thus these rotaxanes should be useful to put our simple model to the test.

EXPERIMENTAL

Kinetics Experiments

NMR spectra for the kinetics experiments were measured on Bruker DRX500 (500 MHz) or AMX400 (400 MHz) spectrometers. All chemical shifts are given in ppm with the solvent signals as internal

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*Corresponding author. E-mail: c.schalley@uni-bonn.de

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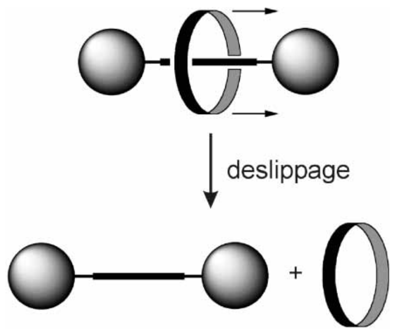
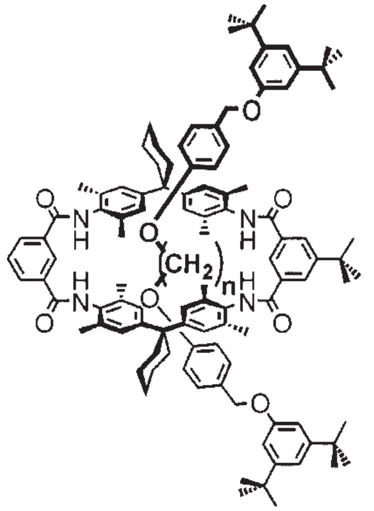


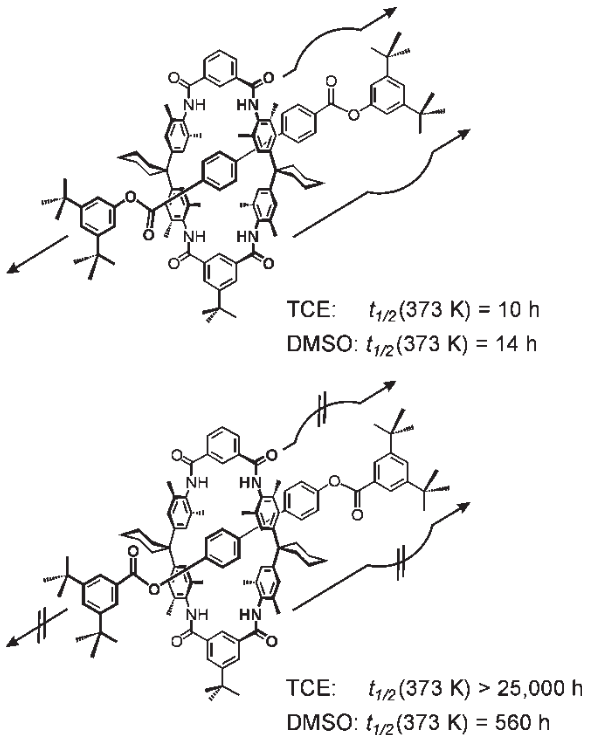
SCHEME 1 Schematic illustration of the deslipping process.



1: *n* = 3
2: *n* = 4
3: *n* = 5
4: *n* = 6
5: *n* = 7
6: *n* = 8
7: *n* = 9
8: *n* = 10
9: *n* = 11
10: *n* = 12

CHART 1 Rotaxanes **1**–**10** under study.

standards. For each of the rotaxanes, the rate constants of the deslipping reaction have been measured at four different temperatures. In preliminary experiments, the temperature range was chosen such that deslipping occurred with a reasonable half life. The NMR samples were then kept in an oil bath at constant temperature. When the half-life was short enough at temperatures accessible with the NMR instrument's heater, the samples were kept in the NMR spectrometer instead. In each experiment, the deslipping was followed until at least 75% of the rotaxane was consumed or until one of the free components precipitated from the NMR solution, whichever occurred first. For the evaluation of the data, the integrations of several signals were averaged wherever possible in order to reduce experimental error. However, some of the rotaxanes exhibit NMR spectra, in which decreasing and increasing signals overlap to such an extent that only one or two of the signals could be safely evaluated. The estimated experimental error range is $\pm$ 4 kJ mol^{-1} for E_A and $\Delta H^{\ddagger}$. Due to the logarithmic plots, the error of k_{∞} and $\Delta S^{\ddagger}$ is somewhat larger and we estimate it to be $\pm$30% for k_{∞} and $\Delta S^{\ddagger}$. The *Arrhenius* activation parameters were derived from a plot of ln k versus $1/T$, while ln (k/T) was plotted versus $1/T$ in order to determine $\Delta H^{\ddagger}$, and $\Delta S^{\ddagger}$ according to the *Eyring* equation. A close inspection of the signals increasing over time confirmed that they correspond to the intact free components and thus exclude decomposition of the axle or wheel rather than deslipping as the reason for rotaxane degradation.



TCE: $t_{1/2}$(373 K) = 10 h
DMSO: $t_{1/2}$(373 K) = 14 h

TCE: $t_{1/2}$(373 K) > 25,000 h
DMSO: $t_{1/2}$(373 K) = 560 h

SCHEME 2 Ester rotaxanes and their half-lives at 373 K in tetrachloroethane (TCE) and dimethylsulfoxide (DMSO). Note that the two structures differ merely with respect to the orientation of the ester groups.

Syntheses

The syntheses, purification, and analytical characterization of all rotaxanes used here have been described earlier [13].

RESULTS AND DISCUSSION

^{1}H NMR experiments can easily be used for following the deslipping reaction of rotaxanes **1**–**10** over time at different temperatures. The aromatic rings in the wheel exert an anisotropy effect on the protons of the axle center pieces, and upfield shifts are usually observed that are also taken as evidence for rotaxane formation. They can be quite significant, and values of up to $\Delta\delta = 1.7$ ppm have been observed [9,10]. Longer axles normally result in smaller values for

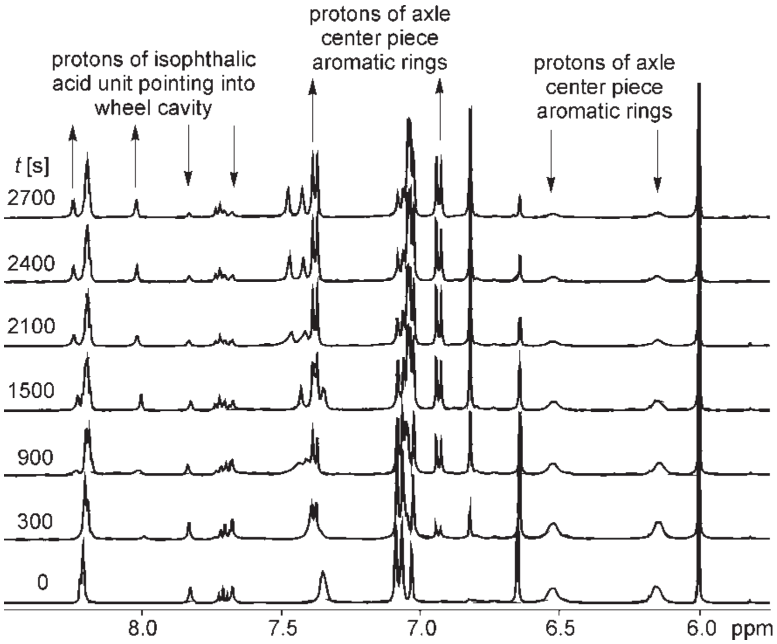


FIGURE 1 Stack plot of NMR spectra of **5** at 393 K. Easily visible are the somewhat broadened signals for the AA′XX′ system of the aromatic protons in the axle center piece. The corresponding signals for the free axle are sharp and appear shifted to lower field by ca. $\Delta\delta = 0.8$ ppm. Smaller, but still significant changes are observed for protons of the wheel, e.g. those of the isophthalic acid moieties pointing into the cavity.

these chemical shift differences, because the wheel moves along the axle quickly and the protons on time average feel the anisotropy to a lower extent compared to rotaxanes with shorter axles [14,15]. In addition, the axles of rotaxanes **1–10** are floppier than those of other previous rotaxanes. Consequently, the upfield shifts are smaller than usual. Nevertheless, they are still large enough to integrate precisely signals for the rotaxane and those of the free components separately so that the deslipping reaction can be easily followed kinetically. Figure 1 shows a series of NMR spectra obtained from rotaxane **5** at 393 K in tetrachloroethane-d_2. Decreasing signals of the rotaxane and growing signals of the free axle can easily be identified. For example, the protons of the aromatic rings at the end of the axle center piece appear as a broadened AA′XX′ system at $\delta = 6.15$ and $\delta = 6.52$ ppm for the rotaxane. Upon deslipping, they decrease and reappear as protons of the free axle at $\delta = 6.85$ and $\delta = 7.38$ ppm which corresponds to a $\Delta\delta$ of ca. 0.8 ppm. Similarly, shifts are observed for protons of the wheel, which feel the axle. The shift differences are however smaller ($\Delta\delta = 0.2$ ppm). Nevertheless, they can still be used to evaluate the deslipping kinetics.

Deslippage is a unimolecular reaction which follows a first-order rate law. Thus, the rate constant k can be derived from the slope of a linear plot of $\ln(c/c_o)$ over the time t with c_o being the initial concentration of the rotaxane and c its concentration at time t (eq. (1)).

$$\ln\frac{c}{c_0} = -kt \tag{1}$$

The rate constants were determined at different temperatures with a temperature range which should not be too small. For the present study the experiments were done between 333 K and 393 K. The activation parameters can then be determined by using the *Arrhenius*equation (eqs. (2) and (3)), which provides the activation energy E_a and the pre-exponential factor A from a plot of $\ln k$ versus $1/T$.

$$k = Ae^{-\frac{E_A}{RT}} \tag{2}$$

$$\ln k = \ln A - \frac{E_A}{RT} \tag{3}$$

Alternatively, the *Gibbs* free enthalpy of activation $\Delta G^{\ddagger}$ or the enthalpy and the entropy of activation $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ are accessible from the *Eyring* equation by plotting $\ln(k/T)$ versus $1/T$. In eqs. (4) and (5), k_B is the *Boltzmann* constant and h the *Planck* quantum.

$$k = \frac{k_B T}{h} e^{-\frac{\Delta G^{\neq}}{RT}} = \frac{k_B T}{h} e^{-\frac{\Delta H^{\neq} - T\Delta S^{\neq}}{RT}} \tag{4}$$

$$\ln\frac{k}{T} = \ln\frac{k_B}{h} + \frac{\Delta S^{\neq}}{R} - \frac{\Delta H^{\neq}}{RT} \tag{5}$$

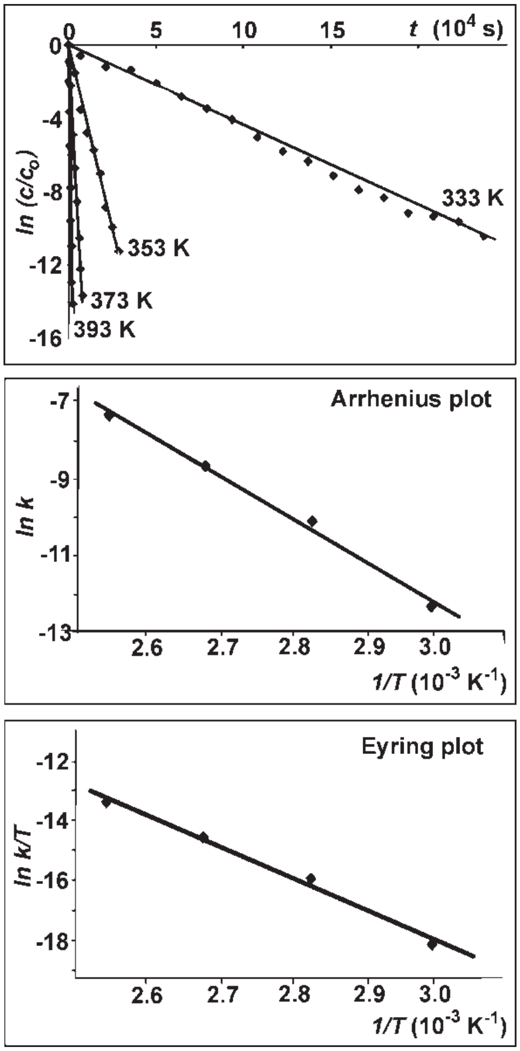


FIGURE 2 Top: Plot of ln *(c/c$_o$)* vs. time *t* for the determination of rate constants at 333, 353, 373 and 393 K. Middle: *Arrhenius* plot of $\ln k$ vs. $1/T$ providing access to the activation energy E_A and the pre-exponential factor *A*. Bottom: *Eyring* plot of ln *(k/T)* vs. $1/T$ for evaluation of the activation enthalpy $\Delta H^{\ddagger}$ and the activation entropy $\Delta S^{\ddagger}$. All plots shown represent the data for rotaxane **4**.

Figure 2 shows the three plots from which the activation parameters can be determined for rotaxane **4** as an example. The activation parameters and the half-life of each of the rotaxanes are summarized in Table I. It should be noted that both ways to evaluate the data provide comparable results, since the *Arrhenius* activation energy E_A contains the enthalpic contributions to the barrier appearing in the *Eyring* equation, while the pre-exponential factor *A* is related to the entropic effects on the barrier. These relations are expressed in eq. (6) and (7) in which T_m is the average temperature of the experimental temperature range [16]. Consequently, the two equations do not provide identical data, but qualitative conclusions are not changed by using one or the other.

$$E_a = \Delta H^{\neq} + RT_m \tag{6}$$

$$A = \frac{k_B T_m}{h}\, e^{\frac{\Delta S^{\neq}}{R}} \tag{7}$$

All rotaxanes **1–10** within experimental error exhibit the same behavior. The half-lives at 373 K all lie within a range between 1 hour and 1 hour 20 minutes; the $\Delta G^{\ddagger}$ values are consequently within a few kJ mol^{-1}. After separating the activation enthalpy from the activation entropy, still the data are consistently close to each other. There is one exception, i.e. rotaxane **8**, but since it does not deviate much from the others with respect to its half-life or free enthalpy of activation, we suspect that the data for this rotaxane are falsely inconsistent with the others.[†] In line with expectation, the data suggest that the chain length of the axle center piece does not have any significant effect on the deslipping kinetics.

CONCLUSIONS

The rotaxanes presented here do not differ with respect to their deslipping kinetics and thus obey the simple model introduced in the introduction. If the axle center piece represents a narrow thread and if no functional groups that could interfere with the deslippage are present, the stopper size indeed governs the deslipping kinetics. The rate-determining step of the deslipping reaction is the passage of the wheel over the stopper. The deslipping reaction has been used for determining steric size, and even the difference between CH_3 and CD_3 groups located at the stopper periphery affected the deslipping rate indicating the precision with which even small effects can be measured [9,10]. This result obtained through isotopic substitution, which affects the rate-determining step of the deslipping reaction confirms the results presented here. However, comparison of the ester rotaxanes depicted in Scheme 2 with the series of rotaxanes **1–10** clearly points to a limitation of this approach. If functional groups are present in the axle which are capable of forming non-covalent interactions with the wheel, they may interfere with the deslippage and alter the kinetics of deslipping. In these cases, care should be taken in interpreting the data. However, these limitations can easily be overcome, when series of rotaxanes are used, which differ merely with respect to one of their features. A comparison of rotaxanes differing significantly in their structures is not recommended.

[†] All rotaxanes in this study have been treated in the same heat baths for the same time intervals in order to ensure good comparability. We have therefore not repeated the measurement for **8** alone. This would probably not provide better data.

TABLE I Activation parameters as obtained from an evaluation of the kinetic data by Arrhenius and Eyring plots and half-life of rotaxanes **1**–**10** at 373 K*

	E_A [kJ mol^{-1}]	A[MHz]	$\Delta G^{\ddagger\dagger}$ [kJ mol^{-1}]	$\Delta H^{\ddagger}$ [kJ mol^{-1}]	$\Delta S^{\ddagger}$ [J K^{-1} mol^{-1}]	$t_{1/2}$ (373 K) [s]
1	93	2468	112	90	−75	3690
2	87	2069	113	90	−76	3560
3	89	541	112	86	−88	4030
4	89	463	113	86	−89	4040
5	88	297	113	85	−93	4710
6	85	364	109	82	−91	4500
7	85	364	109	82	−91	4480
8	77	10	110	74	−121	4330
9	91	2908	116	91	−83	4420
10	90	551	113	87	−87	4530

*All measurements were carried out in tetrachloroethane-d_2 as the solvent. †Free enthalpies of activation were calculated for 298 K.

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References

[1] Schill, G. *Catenanes, Rotaxanes and Knots*; Academic Press: New York, 1971.

[2] *Molecular Catenanes, Rotaxanes, and Knots*; Sauvage, J.-P., Dietrich-Buchecker, C., Eds.; Wiley-VCH: Weinheim, 1999.

[3] Diederich, F.; Stang, P. J. *Templated Organic Synthesis*; Wiley-VCH: Weinheim, 2000.

[4] Kogej, M., Ghosh, P., Schalley, C.A., How to thread a string into the eye of a molecular needle: Template-directed synthesis of mechanically interlocked molecules in: Strategies and Tactics in Organic Synthesis; Harmata, M., (Ed.); Elsevier, in press.

[5] Gibson, H. W.; Liu, S.; Lecavalier, P.; Wu, C.; Shen, Y. X. *J. Am. Chem. Soc.* **1995**, *117*, 852–874.

[6] Raymo, F. M.; Houk, K. N.; Stoddart, J. F. *J. Am. Chem. Soc.* **1998**, *120*, 9318–9322.

[7] Hübner, G.; Nachtsheim, G.; Li, Q.-Y.; Seel, C.; Vögtle, F. *Angew. Chem.* **2000**, *112*, 1315–1318.

[8] Hübner, G.; Nachtsheim, G.; Li, Q.-Y.; Seel, C.; Vögtle, F. *Angew. Chem. Int. Ed.* **2000**, *39*, 1269–1272.

[9] Felder, T.; Schalley, C. A. *Angew. Chem.* **2003**, *115*, 2360–2363.

[10] Felder, T.; Schalley, C. A. *Angew. Chem. Int. Ed.* **2003**, *42*, 2258–2260.

[11] Affeld, A.; Hübner, G. M.; Seel, C.; Schalley, C. A. *Eur. J. Org. Chem.* **2001**, 2877–2890.

[12] Linnartz, P.; Bitter, S.; Schalley, C. A. *Eur. J. Org. Chem.* **2003**, 4819–4829.

[13] Schalley, C. A.; Silva, G.; Nising, C. F.; Linnartz, P. *Helv. Chim. Acta* **2002**, *85*, 1578–1596.

[14] Reuter, C.; Seel, C.; Nieger, M.; Vögtle, F. *Helv. Chim. Acta* **2000**, *83*, 630–640.

[15] Reuter, C.; Mohry, A.; Sobanski, A.; Vögtle, F. *Chem. Eur. J.* **2000**, *6*, 1674–1682.

[16] Frey, H. M.; Walsh, R. *Chem. Rev.* **1969**, *69*, 103–124.