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Sequence-sorted redox-switchable hetero[3]rotaxanes

Marius Gaedke,a Henrik Hupatz,a Felix Witte,b Susanne M. Rupp,c Clara Douglas,b Moritz Malischewski,c Beate Paulusb and Christoph A. Schalley*a

From a library of five crown ether macrocycles with different ring sizes and redox-active moieties, such as tetrathiafulvalene (TTF) and naphthalene diimide (NDI), directional heterocircuit[3]rotaxanes were constructed. Using an axle with two binding sites with different steric accessibility, the concept of integrative self-sorting was applied to program the sequence of functional units in heteropseudo[3]rotaxanes. Depending on binding strength and ring size of the smaller macrocycles, different heteropseudo[3]rotaxane selectivities and stabilities were determined by 2D NMR spectroscopy and tandem mass spectrometry. A heteropseudo[3]rotaxane with rotaxane-like behaviour was isolated chromatographically, displaying electrochemically "frustrated" properties. A robust synthetic procedure was developed allowing the synthesis of four new hetero[3]rotaxanes incorporating specific sequences of functional units. Sequence pseudoisomeric rotaxanes which have the naphthalene diimide subunit at two different positions show distinct electrochemical properties. DFT calculations suggest that this differences could arise from a folding of the structure, in which the redox-active moieties stack with a stopper unit. This study presents a blueprint for the construction of hetero[3]rotaxanes with sequential control of the functional units along the track of the axle and paves the way to extend the functionality of mechanically interlocked molecules.

Introduction

Mechanically interlocked molecules (MIMs) have shown great potential as artificial molecular switches and motors performing various tasks at the nanoscopic level and rudimentarily mimicking functions of natural molecules.1-3 However, the molecular complexity and thereby accessible functions of MIMs are often limited by their symmetrical structures.3-7 The asymmetrical and directional structure of functional biomolecules derives not only from the centrochirality of their molecular building blocks originating from a defined structural pool of building blocks, such as DNA nucleotides or amino acids, but also from the specific sequences in which these building blocks are connected. This sequence induces for example the secondary and tertiary structure formation in proteins.8 The precise positional control of functional units in the natural assembly processes is remarkable. Only minor changes in the sequence can cause a significantly different structure and hence may change function.9 Therefore, the precise control over the directionality and sequence of subcomponents in molecular assemblies is an important goal when constructing functional molecules.

Most MIMs described in the literature are [2]rotaxanes and some examples incorporate directional axles (Fig. 1, top left). Directional axles have been used to build sophisticated molecular machines which operate in a directional fashion. For example, so-called "ribosomal rotaxanes", incorporate a sequence of amino acids on the track of a directional axle. This amino acid sequence is then sequentially connected to a macrocycle upon chemically induced and directional wheel translation.10-12

In a homocircuit[3]rotaxane, two identical macrocycles are threaded onto the axle and a directionality can again only be defined by the axle itself (Fig. 1, top right). Also, oligohomo[\(n\)]rotaxanes containing more than two macrocycles have been described.13-16 In particular, molecular pumps, where multiple macrocycles are threaded onto an axle bringing the system to a higher energy state, are fascinating examples for the application of directional homocircuit[\(n\)]rotaxanes.17-19

If the two threaded macrocycles are not identical, a more complex picture arises. In heterocircuit[3]rotaxanes (Fig. 1, bottom), the directionality is additionally described by the order of macrocycles on the directional axle, consequently, sequence isomers may exist.20-23 As a consequence of their unique structure, the isomer-specific synthesis of heterocircuit-
[3]rotaxanes is not trivial.\textsuperscript{24} Hence, only few examples of heterocircuitrotaxanes have been described yet.\textsuperscript{25} In 1995, the first heterorotaxane synthesis was reported by the group of Stoddart applying a sequential threading approach where a [2]rotaxane is synthesised first. In a second step, the second macrocycle is then threaded onto the axle.\textsuperscript{26} A decade passed with minor advancements in this field due to the synthetic obstacles. However, in the last 15 years the interest in heterocircuitrotaxanes increased and outstanding examples could be realised via new synthetic approaches.\textsuperscript{24, 27-34} The group of Loeb, for example, utilised a sequential threading-clipping method yielding a [3]rotaxane facilitating a ring-through-ring molecular shuttling.\textsuperscript{35}

Fundamentally different are syntheses using the concept of self-sorting. Here, no sequential addition of components defines the sequences, but instead all components are present in one solution, and find their positions in the final structure through the sorting of orthogonal binding motifs.\textsuperscript{36} Even though homorotaxanes or sequence isomers could form, the macrocycles and axles are structurally programmed to prefer one of the heterorotaxane isomers. The group of Goldup, for example, developed a kinetic self-sorting method to obtain heterocircuit[3]rotaxanes.\textsuperscript{37} In 2008, the concept of integrative self-sorting was introduced by us for constructing heterorotaxanes using sufficiently different crown/ammonium binding motifs.\textsuperscript{38, 39} This principle allows to program sequences of two macrocycles on one axle, for example by descending ring size accompanying binding site selectivity.\textsuperscript{40} Later, it was also applied in the synthesis of a [c2]daisy-chain-containing hetero[4]rotaxane\textsuperscript{40} and a hetero[6]rotaxane.\textsuperscript{41} In a time-dependent mass spectrometric study of the self-sorting process, the crucial role of error correction and kinetic path selection was demonstrated.\textsuperscript{42} So far, all examples of heterorotaxane have a narrow scope of macrocycle combinations and are mostly complex assemblies, but do not contain functional or stimuli-responsive units. The precise arrangement of functional units would pave the way to new molecular switches with emerging properties.

In our recent work on redox-active crown/ammonium complexes we observed that the combination of electron donor tetrathiafulvalene (TTF) and electron acceptor naphthalene diimide (NDI) in a divalent rotaxane yielded a donor-acceptor complex.\textsuperscript{43} Furthermore, homooligorotaxanes incorporating TTF-decorated crown ethers enabled the understanding of new switching modes in donor-donor assemblies, such as synchronised pirouetting motion of two macrocycles\textsuperscript{44} and an accordion-like motion of the crown ethers.\textsuperscript{45} In a study on TTF- and NDI-decorated crown ethers with different cavity sizes, crown[8] ethers revealed a preference for dibenzylammonium and crown[7] wheels for benzyl alkyl ammonium stations, suggesting integrative self-sorting for more functional wheels.\textsuperscript{46}

Herein, we propose a blueprint to sequence-sorted heterocircuit[3]rotaxanes using one directional axle and a library of five macrocycles carrying three different types of functional units. This approach allows for unrestricted selection and combination of the functional units in rotaxane structure. We investigate the influence of different ring sizes and binding strengths of the crown ethers involved on the self-sorting equilibrium and heteropseudo[3]rotaxane properties. We apply these findings to the synthesis of four redox-switchable hetero[3]rotaxanes and study the influence of the sequence of functional units on the spectroelectrochemical properties of the rotaxane assemblies.

Results and discussion

Design of molecular building blocks

The macrocycle library consists of three types of functionalised crown[8] ethers and two types of functionalised crown[7] ethers (Fig. 2): While TTFC8 contains an electron-rich pro-aromatic tetrathiafulvalene with electron-donor property (yellow, “donor”), DBC8 and BC7 exhibit an aromatic system with no significant donor or acceptor properties (grey, “neutral”), and NDIC8 and NDIC7 incorporate an electron-poor aromatic system with electron-acceptor properties (green, “acceptor”). The axle Ax contains two secondary ammonium binding stations which are separated by a phenyl group to prevent threading of the crown[7] ethers to the dibenzyl ammonium station (Fig. 2).\textsuperscript{38} The directionality of the axle is not only described by the two binding stations, but also, the di-tert-
butyl stopper. This stopper prevents any wheel threading from this end of the axle and is crucial for programming the wheel sequence. Weakly coordinating tetrakis[3,5-bis(trifluoromethyl)phenyl]borate (BArF$_4$) counternions are used to facilitate a stable threaded complex of the weaker binding crown ethers NDIC8, TTF8 and NDIC7. NDIC7 and axle Ax are novel structures and were synthesised along the procedures given in the supporting information (ESI† section 1). For NDIC7 we obtained a crystal structure (ESI† section 8). In the crystal, the dihedral angle between the phenyl group and the NDIC8 is 70.01(11)$^\circ$, which is considerably flatter than for NDIC7 (84.18(8)$^\circ$), in order to facilitate π-π interactions between the NDIs of neighbouring NDIC7 in the solid state. The ring sizes of NDIC8, NDIC7 and TTF8 are wider than those of DBC8 and BC7, respectively, as the 4.766(6) Å (NDIC7) / 4.730(4) Å (NDIC8) distance of the two phenolic O atoms in the NDI-substituted macrocycles as well as the S-S distance of 3.3136(13) Å in TTF8 are substantially larger than the O-O distance of 2.5642(5) Å in DBC8.47

Recently, we have shown that the spectroelectrochemical properties of redox-active crown ethers are not significantly influenced by the crown ether size.45 This allows us to use the crown ether sizes to program the position of the functional unit on the axle without changing the spectroelectrochemical properties of the functional units. Therefore, the hetero[3]rotaxane combinations carrying DBC8 / NDIC7 and NDIC8 / BC7 are considered as “sequence pseudoisomers”.

The thermodynamics of pseudorotaxane formation has been studied for monovalent model axles by isothermal titration calorimetry, revealing a 10 times stronger binding for DBC8 and BC7 compared to NDIC8 and TTF8, as well as, NDIC7, respectively (for binding data, see ESI† table S1). Crown[8] ethers bind to the aliphatic ammonium slightly weaker than the crown[7] analogues.

**Self-sorting of pseudorotaxanes**

The intermediates and products of the self-assembly of equimolar mixtures of divalent axle and the two differently sized generic crown ethers C8 (pink) and C7 (blue) are shown schematically in Fig. 3a, where homopseudo[3]rotaxane PRBC8C8 and pseudo[2]rotaxane PRC7 represent dead-ends on the way to the desired heteropseudo[3]rotaxane PRBC8C7. Error-correction is necessary to overcome these dead-ends.

For all six combinations of one C8, one C7 and Ax, equimolar solutions were equilibrated for 16 days at room temperature after which no further change in the NMR spectra was observed. Although a full assignment of all signals in the highly complex 1H NMR spectra is not straightforward due to severe signal overlap (ESI† section 3), the four methylene signals (H(4), H(5), H(8) and H(9)) can be identified in the COSY spectra and are highly indicative for pseudorotaxane formation (Fig. 3b, e and ESI† section 3). For the mixture containing TTF8, BC7 and Ax, three major species could be identified and assigned by the chemical shift of their methylene protons to the heteropseudo[3]rotaxane PRTTFBC8C7 (Fig. 3b, blue), homopseudo[3]rotaxane PRTTF8C8C7 (Fig. 3b, red) and pseudo[2]rotaxane PRB8C7 (Fig. 3b, green). Changing the smaller macrocycle to the weaker binding NDIC7 a higher amount of heteropseudo[3]rotaxane PRTTF8C8NDIC7 (Fig. 3e, blue) was observed. While the pseudo[2]rotaxane PRNDIC7 cannot be identified, a small fraction of pseudo[2]rotaxane PRTTF8C8 (Fig. 3e, brown) is visible. The other four combinations show similar results (ESI† section 3). As calculated from the integrals of the methylene protons H(4) and H(5), the heteropseudo[3]rotaxanes are preferentially formed with amounts of 56 – 74% in all six cases (Table 1). For a non-self-sorting system with a directional axle a statistical amount for one specific heteropseudo[3]rotaxane of 25% would be expected. The weaker binding macrocycle NDIC7 forms the corresponding heteropseudo[3]rotaxanes with higher selectivity as compared to BC7.

Due to the charge inherent in all pseudorotaxanes under study, electrospary ionisation mass spectrometry (ESI-MS) is a valuable additional analytical technique to study the self-sorting equilibrium (Fig. 3c, f and ESI† section 4). Due to differences in ionisation efficiencies, the overall abundances cannot be directly related to solution concentrations, yet a semiquantitative overview of the formation of the pseudorotaxanes with reaction time can certainly be obtained. A solution of Ax and TTF8 was equilibrated for 1 h. In the ESI mass spectrum, pseudo[2]rotaxane PRTTF8C8 can be observed in the two +1 and +2 charge states (Fig. 3c). The homopseudo[3]rotaxane PRTTF8C8C7 is not observed in the mass spectrum, as it forms PRTTF8C8 rapidly upon dilution and ionisation due to the low thermodynamic and kinetic stability of PRTTF8C8C7. After addition of BC7, heteropseudo[3]rotaxane PRTTF8C8C7 forms only slowly on an hour time scale, as the threading of BC7 is a slow process. At the same time, also the dead-end pseudo[2]rotaxane PRBC7 is formed.

In marked contrast, hetero[3]pseudorotaxane PRTTF8C8NDIC7 forms already within minutes upon addition of the wider NDIC7 to the solution of Ax and TTF8. After 4 h virtually no changes are observed in the spectrum (Fig. 3f). The same experiments with the other crown[8] ethers revealed that the equilibrium for NDIC7-containing mixtures are reached after a couple of hours, while mixtures including BC7 take several days to equilibrate (Table 1 row 3 and ESI† section 4). This difference can be rationalised by the bigger ring size and thereby faster threading kinetics of NDIC7. Slower threading kinetics come together with a slower error correction process, as it can also be seen by the appearance of dead-end PRBC7 in the mass spectrum as well as the 1H NMR experiments. The different crown[8] ethers do not significantly alter the overall threading kinetics and heteropseudo[3]rotaxane PRBC7 selectivity, as their threading is comparably fast.42

Collision-induced dissociation (CID) experiments with mass-selected heteropseudo[3]rotaxane ions were used to establish the sequence of the pseudorotaxanes and to exclude non-threaded binding (ESI† section 4). For all heteropseudo[3]rotaxanes incorporating NDIC7, the CID mass spectra showed the loss of the crown[7] ether as the first fragmentation step (ESI† Fig. S39–S41). In contrast, BC7 containing heteropseudo[3]rotaxane ions fragment by breaking of a covalent bond first.
(ESI† Fig. S36 – S38). The 50% survival yield voltages $E_{50}$ obtained from the CID mass spectra allow to compare the gas-phase stabilities of the heteropseudo[3]rotaxane assemblies (Fig. 3d, g, Table 1 and ESI† Fig. S42). PRTTFC8BC7 exhibits a significantly higher gas phase stability as compared to PRTTFC8NDIC7 (Fig. 3d, g). Also, $E_{50}$ mainly is impacted by the threaded crown[7] ether (Table 1 row 4). Taking into account, that the isolated ions are doubly charged, the $E_{1/2}$ values of all six heteropseudo[3]rotaxane ions are significantly higher than for a non-threaded crown/sec-ammonium complex. Overall, these observations evidence the desired sequence and threaded structures were achieved in all six heteropseudo[3]rotaxane combinations.

Fig. 3 a) Schematic representation of the self-sorting equilibrium for two generic crown ethers C8 (pink) and C7 (blue). Spectra in (b, c and d) use an equimolar solution of TTFC8, BC7 and Ax; and in (e, f and g) of TTFC8, NDIC7 and Ax. Signals of protons or ions for the heteropseudo[3]rotaxanes are labeled in blue, for the homopseudo[3]rotaxanes in red, for the pseudo[2]rotaxane PRTTFC8 in brown and to the crown[7] pseudo[2]rotaxanes in green. (b, e) Partial $^1$H, $^1$H COSY spectra (700 MHz, CD$_2$Cl$_2$, 298 K, 5 mM, 16 d). For full 1H NMR spectra and integration see Figure S24 and S26. (c, f) Time-dependent ESI-MS spectra in CH$_2$Cl$_2$ at 293 K. Non-labeled peaks correspond to different crown ether ions (ESI† section 4). (d, g) Survival yield curves obtained for mass-selected ions of PRTTFC8BC7 m/z 791 (d) and PRNDIC8BC7 m/z 951 (g) obtained from CID experiments at increasing collision voltages. Solid lines represent a sigmoidal fitting to determine 50% survival yield voltages $E_{50}$ (Table 1 and ESI† section 4).
Table 1 Characterisation parameters for the self-sorting equilibrium of six macrocycle combinations with axle Ax in equimolar solutions obtained by $^1$H NMR spectroscopy, time-dependent and tandem mass spectrometry (for full data set and experimental details see ESI† section 3 and 4).

| macrocycle combination | DBC8 BC7 | TTF8 BC7 | NDIC8 BC7 | DBC8 NDIC7 | TTF8 NDIC7 | NDIC8 NDIC7 |
|-------------------------|---------|---------|-----------|-----------|-----------|-----------|
| hetero[3]pseudorotaxane amount$^a$ | 58% | 56% | 57% | 72% | 70% | 74% |
| threading timeframe$^b$ | days | days | hours | hours | hours | hours |
| $E_{50}^c$ | 21.7 V | 24.7 V | 27.1 V | 9.4 V | 10.9 V | 11.4 V |

$^a$ calculated from signal integration in $^1$H NMR experiments (700 MHz, CD$_2$Cl$_2$, 298 K, 5 mM, 16 d). Amounts are given as percentages of all identified pseudorotaxane species (estimated error: 5%). $^b$ Qualitative estimation from time-dependent ESI-MS, when 90% of the maximum heteropseudo[3]rotaxane concentration is reached. $^c$ Estimated error amounts to 0.5 V.

These results clearly show that the second, smaller macrocycles NDIC7 and BC7 dominate the thermodynamic and kinetic properties of the self-sorting equilibrium. The benefit of faster threading kinetics for a self-sorting process can be highlighted by the observation of a higher selectivity for the NDIC7 containing heteropseudo[3]rotaxanes. The higher binding constants achieved by using BArF$_{24}^-$ counterions compared to previous studies$^{38, 39, 42}$ where PF$_6^-$ counterions were used, caused a higher kinetic barrier for the dethreading reaction of BC7, which is the crucial step for all error-correction processes, resulting in a comparably long equilibration time.

Yet, the used conditions are robust and facilitate the formation of heteropseudo[3]rotaxanes for all combinations.

A cascade-stoppered pseudo[3]rotaxane

The slow self-sorting process together with the remarkably high gas phase stability of BC7-containing heteropseudo[3]rotaxanes motivated us to study PRTTF8BC7 in a greater detail. Although a few exceptions are known,$^{34, 46}$ crown/ammonium pseudorotaxanes are usually not sufficiently stable to survive column chromatography. Therefore, it is surprising that the pseudorotaxane PRTTF8BC7 was chromatographically isolated in 24% yield. For all other

![Fig. 4 $^1$H NMR comparison of free axle Ax, PRTTF8BC7 and RTTF8BC7. Characteristic shifts are highlighted by red dotted lines. (ESI† section 1.4 for full signal assignment)
combinations of wheels under study here, the formed complexes dissociate on the silica column. Pseudo[3]rotaxanes with NDC7 dissociate quickly. The two other BC7-containing pseudo[3]rotaxanes required more polar mobile phases, which undermine their stability so that they also dissociate during chromatography. The stronger binding wheel BC7 on the outer binding site acts as a stopper for the weaker binding wheel TTFC8 on the dibenzyl ammonium binding site. Pseudo[3]rotaxanes of two TTFC8 on Ax could not be isolated as they fell apart during the purification. This underlines the exceptional importance of the sequence in which the macrocycles are threaded on the one-side stopped axle for the physico-chemical properties of the assembly.

For comparison, the rotaxane RTTFCC8BC7 was synthesised in 15% yield by adding 1.5 equiv. of 2,6-dimethoxybenzonitrile oxide to stopper St1 and stirring for one day at 35 °C. Fig. 4 shows the ¹H NMR shifts of (P)RTTFCC8BC7 in comparison to the axle Ax. Characteristic shifts include benzylic methylene protons H(4/5) and H(9), which shift downfield (Δδ ≥ 0.4 ppm and +0.2 ppm) upon threading of TTFC8 and BC7. Additionally, methylene protons H(8) shift upfield by 0.3 ppm. Both is true for the pseudo[3]rotaxane PRTTFCC8BC7 and the [3]rotaxane RTTFCC8BC7. A strong downfield shift by 3.9 ppm of the former alkyne proton H(16) is observed, as it is incorporated into the newly formed isoxazole moiety. The methylene group H(15) adjacent to the former alkyne also shifts by 0.4 ppm downfield. Except for the protons on stopper St1 and H(15,16), the shifts of pseudorotaxane PRTTFCC8BC7 and rotaxane RTTFCC8BC7 are similar.

To test the stability in a more polar solvent, chromatographically isolated PRTTFCC8BC7 was dissolved in acetonitrile in high dilution (1 µM). After 6 h a significant amount of threaded PRTTFCC8BC7 could still be observed by ESI-MS (ESI† Fig. S43). It took multiple days to reach thermodynamic equilibrium in which virtually no complex has survived, evidencing the high kinetic stability and nearly rotaxane-like behaviour of PRTTFCC8BC7.

Electrochemical characterisation of both species (P)RTTFCC8BC7, by cyclic voltammetry (CV) and differential pulse voltammetry (DPV) show similar results (Fig. 5). The two reversible oxidations of TTF are anodically shifted, as expected for wheel TTFC8 bound to an ammonium site.⁴⁶ In previous work, we reported that the ammonium site is expelled upon oxidation due to coulombic repulsion with the oxidised TTFC unit. Electrochemically induced dethreading results in a new signal for the TTF-•+/2+ redox couple of unbound TTFC8 at ~1 V against decamethylferrocene / decamethylferrocenium (Fc•+/2+).⁴⁸ Sterically demanding end groups can kinetically hamper oxidation-induced dethreading efficiently.⁴⁶ However, for both, pseudorotaxane and rotaxane, no dethreading is observed and redox potentials vary only marginally. This underlines the remarkable stability, which is exceptional for a non-interlocked crown/ammonium complex, and rotaxane-like behaviour of PRTTFCC8BC7 as already observed in the CID measurements. The increased TTF oxidation potentials (+ 126 and 362 mV for first and second oxidation) together with its inability to dethread turn PRTTFCC8BC7 into an electrochemically “frustrated” pseudorotaxane that is kinetically trapped in a metastable state.

**Hetero[3]rotaxane synthesis**

The self-sorting experiments show pseudohetero[3]rotaxane formation to be prominent for all C8/C7 macrocycle combinations. We therefore developed a generally applicable synthetic procedure for the synthesis of the corresponding hetero[3]rotaxanes, which does not depend on a prior chromatographic purification of the pseudo[3]rotaxane precursors. The pseudorotaxane mixtures were treated with the 2,6-dimethoxybenzonitrile stopper St1. This reaction was optimised by using up to six equivalents of the smaller macrocycle relative to the axle to reduce homo[3]rotaxane formation to be prominent for all hetero[3]rotaxanes which all feature the diagnostic H NMR shifts of NDIC7 and “neutral-acceptor” (grey-green) hetero[3]rotaxanes. The isolated examples consist of a “donor-acceptor” (yellow-green) and “neutral” (yellow-grey), “donor-acceptor” (yellow-green) and “neutral-acceptor” (grey-green) hetero[3]rotaxanes. The isolated yields compare very well to the majority of isolated heterorotaxanes in the literature.²⁶, ²⁸, ³⁵, ³⁷ Additionally, the isolation of hetero[3]rotaxanes with different wheel
combinations without self-sorting would certainly be a very tedious process.

**Optoelectronic properties of sequence-sorted rotaxanes**

A comparison between isolated hetero[3]rotaxanes and the free macrocycles TTFC8, NDIC7 or NDIC8 allow an assessment of the influence of the macrocycle sequence on the electrochemical properties. Fig. 7 summarises all peak potentials obtained by DPV measurements in 1,2-dichloroethane with n-Bu4NBArF24 as supporting electrolyte (ESI† table S2). The potentials are referenced against the Fc*0/+ redox-couple. The peaks at positive potentials can be attributed to the two reversible redox waves, TTF(0/+1) and TTF(+1/2+). As previously shown, all species with TTFC8 bound to an axle are shifted anodically in a comparable fashion. The second macrocycle does not have strong impact on the oxidation of TTFC8 in the rotaxane as can be seen on the similar oxidation potentials of donor-acceptor rotaxane RTTFC8NDIC7 and donor-neutral rotaxane RTTFC8BC7.

In contrast, the peaks at negative potentials are the two reversible reductions NDI(0/-) and NDI(-1/-2). For the free wheels NDIC7 and NDIC8 both reduction peaks are similar (ΔE1/2 = 11 mV for NDI(0/-) and ΔE1/2 = 16 mV for NDI(-1/-2)), as expected from their similar structures. For [3]rotaxane RNDIC8BC7 a significant cathodic shift of 20 mV for NDI(0/-) and 55 mV for NDI(-1/-2) compared to wheel NDIC8 is observed. In contrast, [3]rotaxanes RTTFC8NDIC7 and RDBC8NDIC7 only show minor differences in the reduction potentials (ΔE1/2 ≤ 10 mV for NDI(0/-) and ΔE1/2 ≤ 11 mV for NDI(-1/-2)) compared to wheel NDIC7. Consequently, the position of the NDI-unit on the axle indeed has a significant impact on the electrochemical properties. For NDIC7 we could not determine a significant influence of the second larger macrocycle neither being neutral nor electron donor. The difference of electrochemical properties of the NDI sequence pseudoisomers RNDIC8BC7 and RDBC8NDIC7 presumably occurs as a consequence of the sequence rather than the macrocycle combination. Indeed, DFT calculations and
understand the exact reason for the different potential shifts of the NDI-unit, the distance of NDI-bearing crown ether to the stopper unit seems to have an influence. Yet, spin-density plots and ESI† section 7). Even though it is rather difficult to calculated structure displays a stacked conformation of TTF-the reduced species (ESI† Fig S60 and S61). Chemical oxidation are TTF-localised for the oxidised species and NDI-localised for dimethoxybenzene stopper (Fig. 8a and ESI† section 7).

We demonstrated how integrative self-sorting can be applied as a molecular programming language to dictate the sequence of redox-switchable units along a molecular track. For the first time, we integrated functional redox-switchable units, namely TTF and NDI, into hetero[3]rotaxanes using this strategy.

Conclusions

The properties of the self-sorting process are dominated by the second macroring in the sequence. While the wider and weaker binding NDIC7 facilitates fast threading kinetics, as well as good hetero[3]rotaxane selectivity, the smaller and stronger binding BC7 results in slow threading kinetics and a slow error correction as well as in lower selectivities for the heteropseudo[3]rotaxane. The BC7-containing hetero[3]rotaxanes show a surprising stability. The pseudorotaxane PRTTF8BC7 could even be isolated by chromatography and thus shows rotaxane-like behaviour with BC7 being a pseudostopper. Upon TTF oxidation, an electrochemically “frustrated” pseudorotaxane forms, in which the larger wheel experiences charge repulsion with the axle ammonium station, but is unable to dethread.

With the synthesis of four new hetero[3]rotaxanes, we demonstrate that different functional units can be placed in different sequences on the axle, as long as one crown[8] ether and one crown[7] ether is used. While for each individual hetero[3]rotaxane combination more selective conditions such as counterion, solvent or equilibration time, can be found, our synthetic approach is general and robust and facilitates the synthesis of hetero[3]rotaxanes with varying crown ether sizes, binding strength and functional units. This concept is applicable to other functionalised crown ethers. By the ease to decorate crown ethers with various functional moieties, our approach represents a modular strategy to incorporate and combine a broad variety of such units using hetero[3]rotaxanes as the scaffold.

In our work the functional units were combined to generate a donor-neutral (RTTFC8BC7), a donor-acceptor (RTTF8NDIC7), an acceptor-neutral (RNDIC8BC7) and a neutral-acceptor (RDIC8NDIC7) rotaxane. Studying the electrochemical properties of these assemes, we could show that the donor moiety (TTF) was marginally influenced. Instead, the acceptor moiety (NDI) showed shifted redox potentials depending on the position on the axle, probably depending on the availability of interactions to one of the stoppers. Regardless of their sequence, the redox-active units retain their reversible spectroelectrochemical properties upon incorporation into the mechanically interlocked structure. Using these results, highly directional functional molecules bearing different macroringes can be envisioned and facilitate new switching modes or functions for rotaxane assemblies.

Author contributions

The project was developed by H. H. and M.G.. The synthetic work was done by F. W. and B. P.. S. M. R. and M. M. measured NMR and tandem MS experiments. M. G. performed further work was done by F. W. and B. P.. S. M. R. and M. M. measured and solved the SCXRD data. Both M. G. and H. H. contributed...
equally and have the right to list their name first in their CV. All Authors contributed to the final version of the manuscript.

Conflicts of interest

There are no conflicts to declare.

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