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Self-assembled orthoester cryptands: orthoester scope, post-functionalization, kinetic locking and tunable degradation kinetics†

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Dynamic adaptability and biodegradability are key features of functional, 21st century host–guest systems. We have recently discovered a class of tripodal supramolecular hosts, in which two orthoesters act as constitutionally dynamic bridgeheads. Having previously demonstrated the adaptive nature of these hosts, we now report the synthesis and characterization – including eight solid state structures – of a diverse set of orthoester cages, which provides evidence for the broad scope of this new host class. With the same set of compounds, we demonstrated that the rates of orthoester exchange and hydrolysis can be tuned over a remarkably wide range, from rapid hydrolysis at pH 8 to nearly inert at pH 1, and that the Taft parameter of the orthoester substituent allows an adequate prediction of the reaction kinetics. Moreover, the synthesis of an alkyne-capped cryptand enabled the post-functionalization of orthoester cryptands by Sonogashira and CuAAC “click” reactions. The methylation of the resulting triazole furnished a cryptate that was kinetically inert towards orthoester exchange and hydrolysis at pH > 1, which is equivalent to the “turnoff” of constitutionally dynamic imines by means of reduction. These findings indicate that orthoester cages may be more broadly useful than anticipated, e.g. as drug delivery agents with precisely tunable biodegradability or, thanks to the kinetic locking strategy, as ion sensors.

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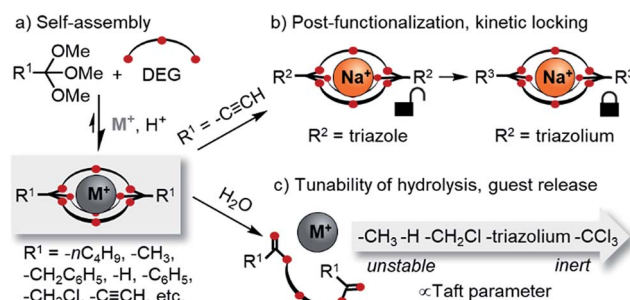
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Introduction

The development of new macro(bi)cyclic compounds has been a key driving force of progress in supramolecular chemistry.¹ The discovery of pillararenes,² for instance, has opened up new avenues in supramolecular polymer chemistry,³ and the rational design of cyanostar⁴ and triazolophane macrocycles⁵ enabled remarkable binding affinities for hard-to-bind anions such as PF₆[−], as well as unprecedented rotaxane syntheses^{6a,6} and fundamental insights on the nature of hydrogen bonding.⁷ In this article, we follow up on our discovery of a new class of self-assembled macrobicyclic host⁸ and report comprehensive data on the scope, structure and properties of these compounds (Scheme 1).

Dynamic combinatorial chemistry⁹ has been used extensively for generating macrocycles and cages from smaller sub-components,^{9g,10} yet prior to our discovery of orthoester cryptands,⁸ there were only few reports on the self-assembly of purely organic dynamic covalent cages suitable to encapsulate

single¹¹ cationic¹² or anionic¹³ guests. Self-assembled macrobicyclic hosts beyond dynamic covalent chemistry have been reported, most notably metallasupramolecular cryptates¹⁴ as well as clathrochelates.¹⁵ However, these compounds share with conventional cryptands the feature that their host framework is no longer dynamic and stimuli-responsive once the self-assembly process is complete. This is different for orthoester cryptands, which under anhydrous acidic conditions are adaptive to their environment,¹⁶ which allowed us to demonstrate that a wide range of metal ions selectively directs the self-assembly of their thermodynamically preferred host.¹⁷

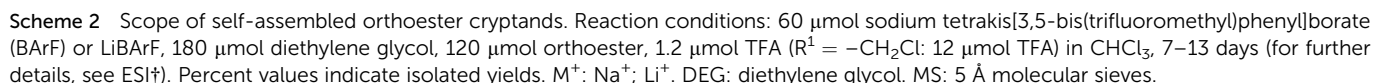


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Scheme 1 Overview on the scope of this study. (a) Template-directed self-assembly of orthoester cryptates: scope of orthoesters (R^1) investigated in this contribution; (b) post-functionalization (R^2) and kinetic locking (R^3) of orthoester cryptates; (c) tunability of the degradation kinetics. DEG: diethylene glycol. M^+ in this work: Na^+ or Li^+ .





Herein, we report a comprehensive study on the scope and generality of self-assembled orthoester cryptands (Scheme 1a) as well as their post-functionalization and post-synthetic stabilization against hydrolysis or exchange reactions (“kinetic locking”, Scheme 1b). Moreover, we explored the question to which extent the kinetics of orthoester exchange and hydrolysis can be tuned as a function of different orthoester substituents and whether the observed trends can be rationalized on the basis of linear free energy relationships (Scheme 1c).²²

Scope of orthoester cryptand self-assembly

By optimizing our procedures for preparing anhydrous starting materials (see ESI[†]), we were able to minimize the undesired hydrolysis of orthoesters to esters and to improve the isolated yield of previously reported orthoacetate cryptate $[\text{Na}^+ \text{ } o\text{-(CH}_3)_2\text{-1.1.1}]^8$ from 67% to 77%. Yields in the range of 50% to 92% were obtained for five new orthoester cryptates (R^1

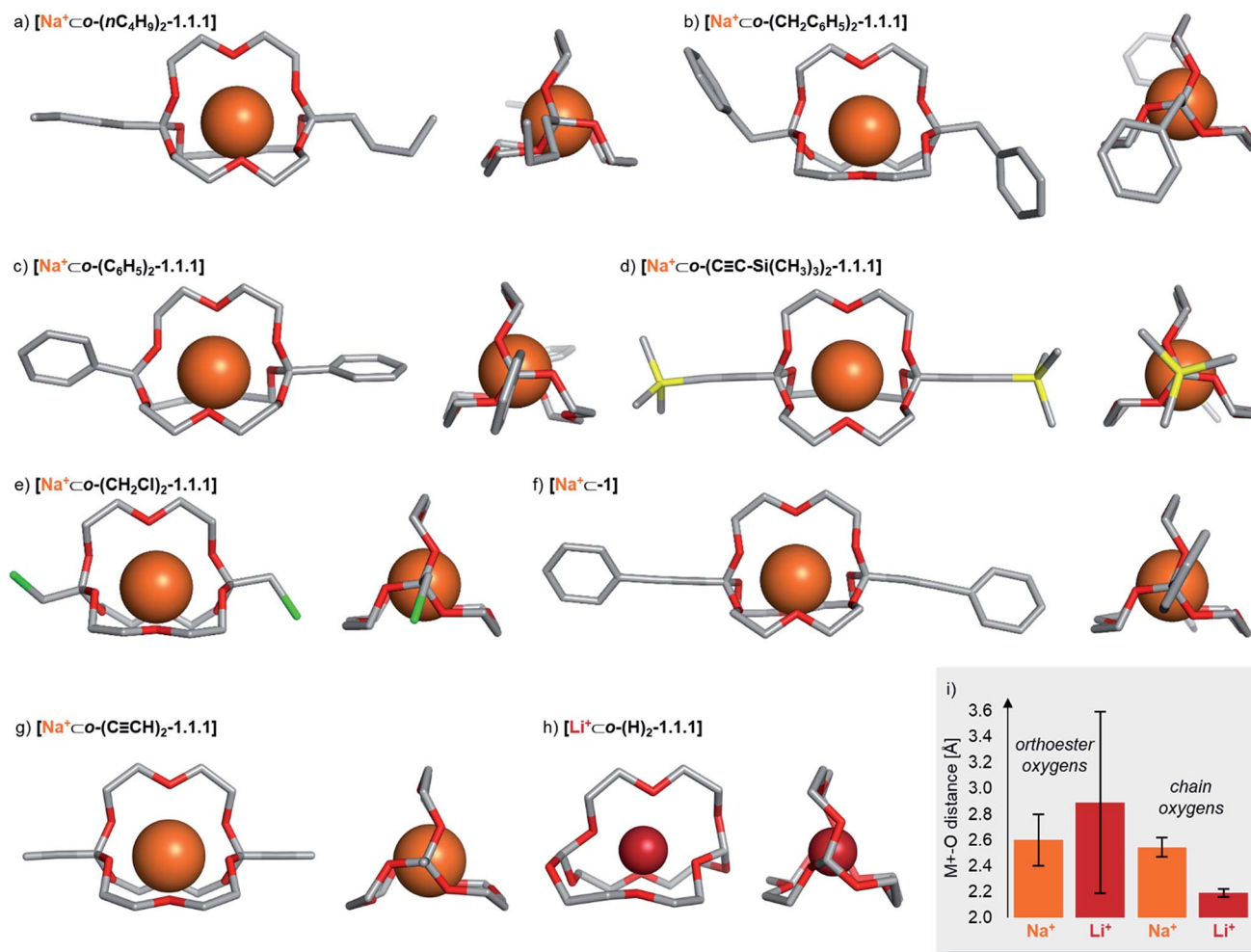


Chart 1 Solid-state structures of eight orthoester cryptands. Single crystals were obtained by the layering method (hexane/chloroform). Hydrogen atoms, anions, solvent and disorder (where applicable) are omitted for clarity. Metal ions are displayed at 100% of effective ionic radius.²⁷ (a) Crystal system: triclinic. Na–O distance (orthoester oxygen): 2.45–2.92 Å. Na–O distance (chain oxygen): 2.48–2.53 Å. (b) Crystal system: monoclinic. Na–O distance (orthoester oxygen): 2.47–2.76 Å. Na–O distance (chain oxygen): 2.51–2.57 Å. (c) Crystal system: orthorhombic. Na–O distance (orthoester oxygen): 2.32–3.53 Å. Na–O distance (chain oxygen): 2.37–2.46 Å. (d) Crystal system: triclinic. Na–O distance (orthoester oxygen): 2.48–2.59 Å. Na–O distance (chain oxygen): 2.54–2.67 Å. (e) Crystal system: monoclinic. Na–O distance (orthoester oxygen): 2.47–2.89 Å. Na–O distance (chain oxygen): 2.48–2.57 Å. (f) Crystal system: triclinic. Na–O distance (orthoester oxygen): 2.43–2.69 Å. Na–O distance (chain oxygen): 2.56–2.61 Å. (g) Crystal system: triclinic. Na–O distance (orthoester oxygen): 2.46–2.66 Å. Na–O distance (chain oxygen): 2.53–2.67 Å. (h) Crystal system: orthorhombic. Li–O distance (orthoester oxygen): 1.96–3.67 Å. Li–O distance (chain oxygen): 2.16–2.23 Å. (i) Comparison of average Na–O distance of all sodium-based solid-state structures with average Li–O distance in [Li⁺⊂o-(H)₂-1.1.1], including standard deviation. For further details, see ESI.†

We were also able to obtain X-ray crystallographic data on a cryptate encapsulating a lithium ion for the first time. Numerous previous attempts at crystallizing [Li⁺⊂o-(CH₃)₂-1.1.1] had been met with failure, presumably due to the relatively low binding constant (Table 1) and (degenerate) binding dynamics in this host.²⁵ In stark contrast to the sodium-based structures, cryptate [Li⁺⊂o-(H)₂-1.1.1] features only five Li–O bonds. This binding mode leads to rather short Li–O bonds of the three chain oxygen atoms (2.16–2.23 Å) and even shorter contacts for the two orthoester oxygen atoms that are involved in Li–O bonds (1.96 Å). Hence, the remaining four orthoester oxygen atoms are significantly more distant (2.94–3.67 Å) than in the sodium-containing solid state structures (see Chart 1i). The crystal system observed for [Li⁺⊂o-(H)₂-1.1.1] is orthorhombic (*P*₂₁₂₁₂₁).

Kinetics of orthoester exchange and hydrolysis

To shed light on the differences in reactivity and stability of orthoesters and their corresponding cryptands, we decided to investigate the kinetics of the exchange reactions of a diverse set of orthoesters with ethanol (see Table 2). To this end, 13 trimethyl orthoesters (**A**₃) were treated with three equivalents of ethanol (**B**) and acid catalyst under standardized conditions and the reaction progress was monitored for up to 16 hours by ¹H NMR spectroscopy. To account for the vast differences in reactivity between the orthoesters, both the amount of acid, as well as the type of acid had to be varied. For example, the CCl₃– and CF₃–substituted orthoesters were found to be so inert that even large quantities of trifluoroacetic acid did not lead to



Table 2 Kinetics and scope of orthoester exchange^a

Acid	R ¹	<i>t</i> ^b [min]	Product ratio (A ₃ : A ₂ B : AB ₂ : B ₃)	Taft ²²
0.01% TFA	– <i>n</i> C ₄ H ₉	10	n.d.	–0.13
0.01% TFA	–CH ₃	280	26 : 44 : 24 : 6	0.00
0.1% TFA	–CH ₂ C ₆ H ₅	650	23 : 41 : 29 : 6	0.22
1% TFA	–H	40	19 : 43 : 31 : 7	0.49
1% TFA	–C ₆ H ₅	50	23 : 42 : 27 : 7	0.60
1% TFA	–C≡C–TMS	90	22 : 41 : 29 : 7	—
1% TFA	–Triazole ^c	130	n.d.	—
1% TFA	–CH ₂ Cl	640	16 : 42 : 32 : 10	1.05
10% TFA	–C≡CH	300	32 : 35 : 26 : 6	2.18
50% TFOH	–CCl ₃	330	n.d.	2.65
50% TFOH	–Triazolium ^d	490	16 : 39 : 33 : 11	—
100% TFOH	–CF ₃	>1000	n.d.	2.61
100% TFOH	–CN		Decomposition	3.30

^a Reaction conditions: orthoester (A₃, 37.5 μmol, 1.0 equiv.), alcohol (B, 112.5 μmol, 3.0 equiv.), internal standard (9.41 μmol) and acid catalyst (0.01 to 100 mol%) were added to the reaction vessel from stock solutions. CDCl₃ was added to obtain a total volume of 750 μL. The reaction was monitored by ¹H NMR spectroscopy. ^b *t*: equilibration time, defined as data point when 99% conversion to plateau-level of methanol A was exceeded for the first time; n.d.: not determined due to peak overlap in NMR spectrum. Estimated error: ±5%. ^c 1-Benzyl-4-(trimethoxymethyl)-1*H*-1,2,3-triazole.

^d 1-Benzyl-3-methyl-4-(trimethoxymethyl)-1*H*-1,2,3-triazol-3-ium.

discernible exchange products. Hence, whenever an orthoester was found to be too inert to react within 16 h under mild reaction conditions, the next harsher set of reaction conditions was investigated (and so on). Besides this step-wise enhancement of acid catalysis, the second crucial parameter in Table 2 is the equilibration time *t*, which we defined as the first data point at which ≥99% conversion to the equilibrium distribution was reached based on ¹H NMR integration. The kinetic data allowed us to order the 13 studied orthoesters from most reactive to most inert (top to bottom in Table 2).

A comparison of the equilibration times reveals that electron-rich orthoesters are vastly more reactive than electron-deficient orthoesters and that the reactivity of orthoesters can be fine-tuned over a remarkably wide range. For instance, trimethyl orthoalvalerate (R¹ = –*n*C₄H₉, see Table 2) equilibrates with ethanol in only 13 min with 0.01% TFA, whereas the reaction of 1,1,1-trifluoro-2,2,2-trimethoxyethane (R¹ = –CF₃, see Table 2) did not reach equilibrium after 16 h, even with 100 mol% trifluoromethanesulfonic acid (TfOH).

Because the results summarized in Table 2 represent the first account of a reactivity sequence for orthoester exchange, we attempted to identify a linear free energy relationship (LFER) that would correlate with the observed trend. We quickly noticed that the Hammett substituent parameter (σ) and

variations thereof are a poor fit, which is not too surprising given that the Hammett reference reaction is rather unlike orthoester exchange. As can be deduced from Table 2, the Taft parameter for the R¹ group does, however, correlate very well with the observed reactivity trend with the only exception (CCl₃ vs. CF₃, see Table 2) being based on a very narrow margin and not relevant to templated cryptate self-assembly. From a mechanistic perspective, this finding makes good sense, because the Taft LFER is based on the acid-catalysed hydrolysis of aliphatic esters, which proceeds *via* the same oxonium intermediates as orthoester exchange.²⁸ Because many orthoester derivatives are commercially available, this correlation with the Taft LFER will be very valuable for designing and optimizing future self-assemblies based on orthoester exchange.

In respect to the scope of self-assembled orthoester cryptates (*vide supra*), these results imply that there is a threshold where self-assembly is no longer possible, because the R¹ substituent is too strongly electron-withdrawing and that this threshold lies between –CH₂Cl (Taft 1.05, see Table 2) and –C≡CH (Taft 2.18, see Table 2). Nevertheless, we would like to emphasize that cryptands equipped with functional groups with Taft values > 1 are accessible *via* post-functionalization methods (*e.g.* R¹ = –C≡CH by deprotection or –triazolium by methylation, *vide infra*).

When considering the thermodynamic, rather than kinetic implications of these results, it is evident from Table 2 that the observed equilibrium compositions (A₃ : A₂B : AB₂ : B₃) are mostly unaffected by the R¹ substituent and the acid catalyst. Yet to our surprise, when plotting the evolution of individual species over time, we found that the thermodynamically least favoured product (B₃) generally reaches its plateau level first. This finding can be rationalized by conflicting steric and electronic effects: the sterically more demanding ethyl group makes B₃ the thermodynamically least stable product, yet the oxonium ion that leads to the formation of B₃ is the most stable intermediate, which means that the conversion of A₂B into AB₂ is slower than the conversion of AB₂ into B₃. See ESI† for further details and kinetic simulations of this interesting “bottleneck” in the evolution of the chemical network over time,²⁹ including the exchange reaction with 2-chloroethanol, which confirms the above reasoning.

In view of possible applications of orthoester cryptates in drug delivery,^{19,30} we turned our attention towards the hydrolytic degradation of orthoesters and the corresponding self-assembled cryptands (Table 3). Six representative orthoesters were dissolved in phosphate buffer solutions of varying pH. The reactions were monitored by ¹H NMR spectroscopy to determine the half-life *t*_{1/2} and the kinetic rate *k*_{obs} of the hydrolysis reaction under pseudo first order conditions. As expected, the kinetics of orthoester hydrolysis follow the same trend that was observed for orthoester exchange. While electron-rich orthoesters (*e.g.*, R¹ = –CH₃, see Table 3, entry 1) hydrolyze readily even at neutral pH, more electron-deficient orthoesters (*e.g.*, R¹ = –triazolium, –CCl₃, see Table 3, entries 5 and 6) are remarkably stable: even at pH 1 their half-lives are beyond 16 h. In the context of drug delivery, we believe that orthoformates (R¹ = –H; *t*_{1/2} 70 min at pH 6, see Table 3, entry 2) and



Table 3 Hydrolysis of orthoesters and a representative orthoester cryptand^a

1A₃

o-(CH₃)₂-1.1.1

Entry	R ¹		pH 8	pH 7	pH 6	pH 5	pH 4	pH 3	pH 1
1	-CH ₃	<i>t</i> _{1/2} [min], <i>k</i> _{obs} [s ⁻¹]	60, 1.8 × 10 ⁻⁴	10, 1.3 × 10 ⁻³	2, 6.1 × 10 ⁻³	<1			
2	-H	<i>t</i> _{1/2} [min], <i>k</i> _{obs} [s ⁻¹]	>1000	510, 2.5 × 10 ⁻⁵	70, 1.6 × 10 ⁻⁴	20, 8.8 × 10 ⁻⁴	7, 2.0 × 10 ⁻³	<1	
3	-CH ₂ Cl	<i>t</i> _{1/2} [min], <i>k</i> _{obs} [s ⁻¹]		>1000	660, 1.7 × 10 ⁻⁵	120, 8.6 × 10 ⁻⁵	30, 2.9 × 10 ⁻⁴	<1	
4	-Triazole ^b	<i>t</i> _{1/2} [min]							<1 ^c
5	-Triazolium ^d	<i>t</i> _{1/2} [min], <i>k</i> _{obs} [s ⁻¹]						Inert	>10 000, 1.6 × 10 ⁻⁶
6	-CCl ₃	<i>t</i> _{1/2} [min]							>1000 ^c
7	o-(CH₃)₂-1.1.1	<i>t</i> _{1/2} [min], <i>k</i> _{obs} [s ⁻¹]		30, 3.5 × 10 ⁻⁴					

^a Reaction conditions: orthoester (**A**₃, 37.5 μmol) or cryptand (**o-(CH₃)₂-1.1.1**, 18.75 μmol) and internal standard (12.3 μmol) were added to the reaction vessel. Buffer solution was added to obtain a total volume of 750 μL. The reaction was monitored by ¹H NMR spectroscopy. *t*_{1/2}: half-life of starting material, defined as point when 50% of starting material were consumed. Estimated error: ±4%. ^b 1-Benzyl-4-(trimethoxymethyl)-1*H*-1,2,3-triazole. ^c 400 μL DMSO added to increase solubility of starting material. Comparison of measurements in pure buffer and with addition of DMSO revealed that *k*_{obs} is decreased by *ca.* one order of magnitude upon addition of the co-solvent (for further details, see ESI).

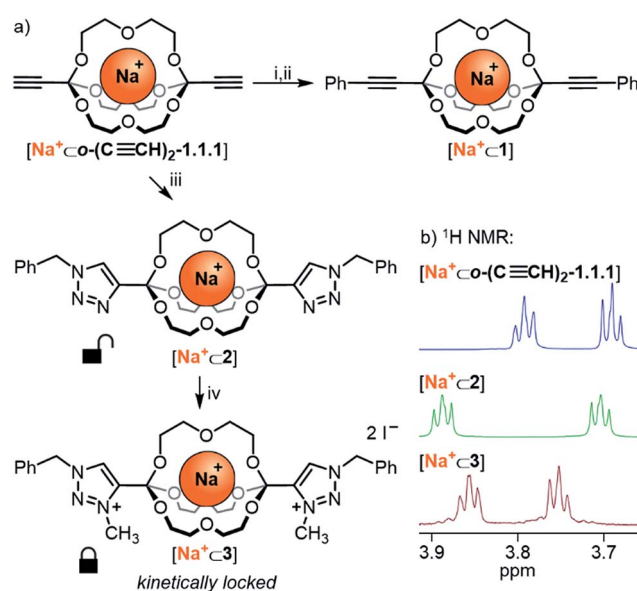
^d 1-Benzyl-3-methyl-4-(trimethoxymethyl)-1*H*-1,2,3-triazol-3-ium.

chloromethyl-substituted orthoesters (R¹ = -CH₂Cl; *t*_{1/2} 121 min at pH 5 and 34 min at pH 4, see Table 3, entry 3) offer the most appealing hydrolysis profiles. ¶

Finally, we monitored the hydrolysis of cryptand **o-(CH₃)₂-1.1.1** under comparable reaction conditions (see Table 3, entry 7). As anticipated,⁸ the observed hydrolysis rate for cryptand **o-(CH₃)₂-1.1.1** is somewhat lower than that for the simple orthoester but in the same range, indicating that our kinetic findings are transferable from orthoesters to orthoester cryptands.

Post-functionalization and kinetic locking of orthoester cryptands

Having established the broad scope and the kinetic limitations of the self-assembly reaction, we turned our attention towards further diversifying orthoester cryptates by post-functionalization (see Scheme 3a).³¹ Cryptate [Na⁺⊂**o-(C≡CH)₂-1.1.1**], containing two functional alkyne handles, was subjected to a Sonogashira reaction with iodobenzene to furnish cryptand **1** in 94% yield. The basicity of the reaction conditions had the advantageous effect that no orthoester hydrolysis was observed, but also led to decomplexation, thus requiring a trivial second step to reintroduce the sodium guest, thus furnishing cryptate [Na⁺⊂**1**]. We believe that this type of reaction will be particularly useful for the preparation of intriguing degradable 1D polymers and for applications in ion sensing, because the aromatic substituents are in conjugation



Scheme 3 Post-functionalization of orthoester cryptands. (a) Reaction conditions: (i) [Na⁺⊂**o-(C≡CH)₂-1.1.1**] (11.8 μmol, 1.0 equiv.), iodobenzene (23.6 μmol, 2.0 equiv.), NEt₃ (35.4 μmol, 3.0 equiv.), CuI (0.12 μmol, 0.01 equiv.), Pd(PPh₃)₄ (0.12 μmol, 0.01 equiv.), THF, 40 °C, 4 d, 94%. (ii) **1** (9.28 μmol, 1.0 equiv.), NaBARf (9.28 μmol, 1.0 equiv.), CH₃CN, r.t., 5 min, quant. (iii) [Na⁺⊂**o-(C≡CH)₂-1.1.1**] (11.0 μmol, 1.0 equiv.), benzyl azide (22.0 μmol, 2.0 equiv.), Cu(MeCN)₄PF₆ (0.11 μmol, 0.01 equiv.), TBTA (0.11 μmol, 0.01 equiv.), MeOH, 70 °C, 24 h, 92%. (iv) [Na⁺⊂**2**] (3.9 μmol, 1.0 equiv.), MeI (excess), MeCN, 70 °C, 3 d, 83%. (b) Partial ¹H NMR stacked plot (500 MHz, 298 K, CD₃CN).



with the orthoester bridgeheads. The introduction of conjugated chromophores or fluorophores should result in pronounced differences in optical output depending on the nature of guest ions, and could also provide a theranostic readout³² for cage degradation and concomitant guest release.

An alternative method for post-functionalization was investigated by the CuAAC “click” reaction between $[\text{Na}^+\text{C}\equiv\text{C}(\text{C}\equiv\text{CH})_2\text{-1.1.1}]$ and benzyl azide. This reaction proceeded in protocol, the product cryptate $[\text{Na}^+\text{C}\equiv\text{C}2]$ was obtained in excellent yield (92%), and in contrast to the Sonogashira reaction without decomplexation of the metal guest. Although electronic communication between substituents and cage is likely weak in such bis-triazoles,³³ we believe that this type of functionalization will prove valuable for installing functional moieties, for example for modulating lipophilicity, targeting biological binding motifs³⁴ or stimuli-responsive triggering of cage decomposition.³⁵

Encouraged by the efficient post-functionalization reactions and the observed differences in hydrolysis rates (Table 3), we wondered whether we could drastically stabilize compound $[\text{Na}^+\text{C}\equiv\text{C}2]$ by methylation of the triazoles.³⁶ At least in principle, the electron-withdrawing effect of the resulting triazolium on the orthoester bridgehead could lead to significantly reduced orthoester reactivity and pave the way towards applications of orthoester cryptands that require stability in water. As shown in Scheme 3a, treatment of $[\text{Na}^+\text{C}\equiv\text{C}2]$ with an excess of iodomethane furnished the corresponding bis-triazolium cryptate $[\text{Na}^+\text{C}\equiv\text{C}3]$ in 83% yield (Scheme 3a, bottom). In proof-of-principle experiments, the corresponding triazolium-substituted orthoester indeed proved to be inert towards hydrolysis at pH 3 (Table 3, entry 5) and underwent orthoester exchange only with 50% triflic acid (Table 2). At pH 1 the half-life for hydrolysis was beyond 16 h, whereas all other orthoesters suitable to prepare cryptates hydrolyzed rapidly under these conditions. The extrapolated half-life of the triazolium-orthoester in fact exceeded 10 000 min, whereas the half-life of the triazole-orthoester is below one minute, which accounts for an increase in stability of at least four orders of magnitude (Table 3, entries 4 and 5). As such, this post-stabilization method is akin to the kinetic locking of imines by means of reduction to the corresponding amines, which has found widespread use in the synthesis of mechanically interlocked molecules, organic cages, porous materials and other applications of dynamic covalent chemistry.³⁷

Conclusions

In this work, we have demonstrated that orthoester cryptands equipped with a broad range of substituents are accessible in one step *via* efficient, metal-templated self-assembly reactions. Cryptands substituted with strongly electron-withdrawing groups could not be obtained, but this limitation was circumvented by highly efficient post-functionalization methodologies based on a Sonogashira or CuAAC reaction of the bis-alkynyl cryptate. Methylation of a triazole-substituted cryptate furnished a supramolecular host that can be considered kinetically locked in respect to orthoester exchange and hydrolysis, but still

binds effectively to cationic guests. In future studies, it could be beneficial to reverse this “locking” by site-selective *N*-dealkylation, which appears to be possible under relatively mild basic conditions.³⁸ We also carried out detailed, comparative kinetic studies on orthoester exchange and hydrolysis, firmly establishing that the tunability of orthoester degradation makes these architectures interesting candidates for the (topical) delivery of ionic drugs, which strictly requires the biodegradability of otherwise toxic supramolecular hosts.³⁹ Further studies on (an)ion encapsulation, sensing, transport and release are underway in our laboratory.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

‡ In principle, oxonium ions of alkynyl-substituted orthoesters could undergo 1,4-addition with alcohol nucleophiles, thus generating tetrasubstituted allene derivatives. However, our results suggest that such side reactions do not occur. For instance, the orthoester with $\text{R}^1 = -\text{C}\equiv\text{CH}$ undergoes clean exchange in the presence of 10% TFA (Table 2).

§ NMR titrations had to be carried out in acetonitrile to guarantee fast exchange on the NMR timescale, as well as sufficient solubility of all starting materials.

¶ The toxicity profile of all possible hydrolysis products will need to be considered for applications in drug delivery. For instance, DEG will likely have to be replaced with a less toxic derivative (proof-of-principle reported in ref. 17) and $\text{R}^1 = \text{CH}_2\text{Cl}$ might pose a major liability due to the potential formation of toxic chloroacetic acid.

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