Novel Annulene Dications from Methylated [2.2]Metacyclophane Monoenes and [e]-Ring Benzannelated Dimethyldihydropyrene

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Tetramethyl- and hexamethyl-substituted [2.2]metacyclophane monoenes (**10** and **11**) are transformed into their corresponding *trans*-dimethyldihydroethanophenanthrenium dications (**14**$^{2+}$ and **15**$^{2+}$) in FSO$_3$H·SbF$_5$ (4:1) and FSO$_3$H·SbF$_5$ (1:1) with SO$_2$ClF or SO$_2$ as the solvent; these 10π-dications are equivalent to the C-4/C-5 diprotonated dications of the 2,7-dimethyl derivative of *trans*-DMDHP, **3a**. The *trans*-12c,12d-dimethyl-12c,12d-dihydrobenzo[e]pyrene (**6**) reacts with FSO$_3$H/SO$_2$ClF under surprisingly mild conditions to give initially a persistent diprotonated dication (**6**H$_2$$^{2+}$) and, subsequently, the oxidation dication (**6**$^{2+}$); the **6**$^{2+}$:**6**H$_2$$^{2+}$ ratio reaches 4:1 after 1 week at low temperature. Protonation of the *anti*-metacyclophane (**13**) was also examined. Charge delocalization mode and tropicity in the resulting dications are gauged via detailed NMR studies at 500 MHz.

Introduction

Cyclophane dienes are important intermediates in the synthesis of dihydropyrenes via the Stevens rearrangement−Hoffmann elimination sequence.[1] Whereas, the anti-8,16-dimethyl derivative (**1**) (Figure 1) spontaneously converts thermally at rt to *trans*-dimethyldihydropyrene (DMDHP, **3**), the parent diene (**2**) is stable, though it isomerizes when it is warmed.[1] Compound **3** has developed into a sensitive probe of ring-current effects because the methyl groups, dangling in the center, respond to variations in bond alternation and localization.[2−5] Synthesis and relative diatropicity of the substituted, benzannelated, and ring-fused derivatives of **3** continue to receive attention,[2−5] as does the interplay between cyclophane dienes and dimethyldihydropyrenes via valence isomerism.[6]
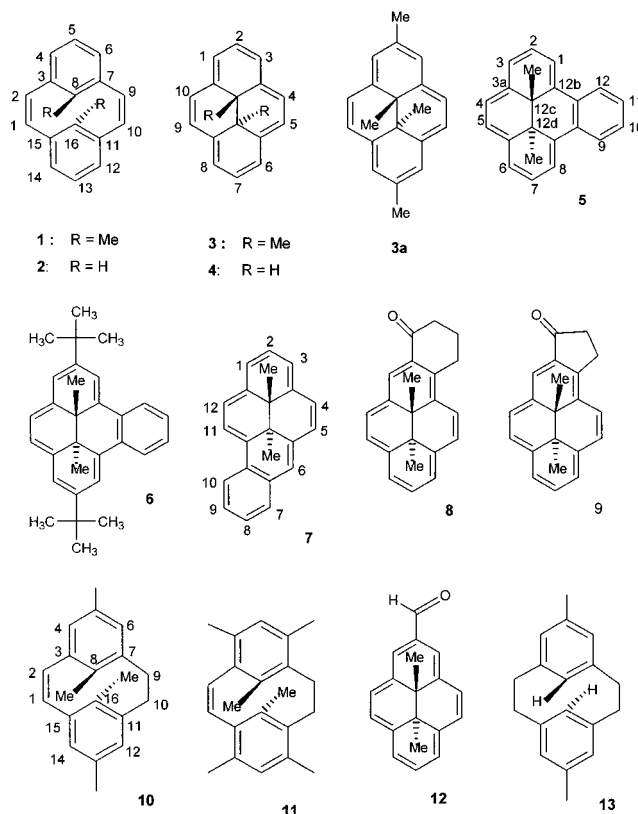
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(1) (a) Mitchell, R. H.; Boekelheide, V. *J. Am. Chem. Soc.* **1974**, *96*, 1547. (b) Vögtle, F. *Cyclophane Chemistry*; Wiley: New York, 1995; Chapter 2.
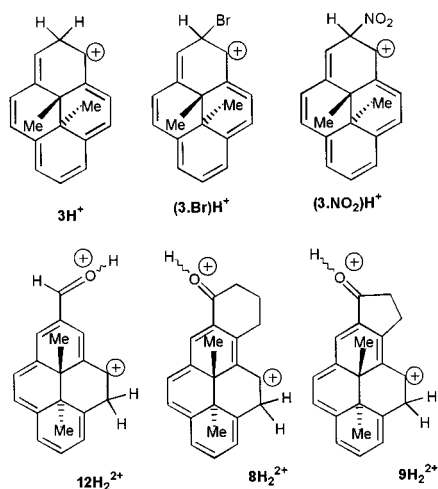
(2) (a) Mitchell, R. H.; Carruthers, R. J.; Mazuch, L.; Dingle, T. W. *J. Am. Chem. Soc.* **1982**, *104*, 2544. (b) Mitchell, R. H.; Williams, R. V.; Dingle, T. W. *J. Am. Chem. Soc.* **1982**, *104*, 2560. (c) Mitchell, R. H.; Williams, R. V.; Mahadevan, R.; Lai, Y.-H.; Dingle, T. W. *J. Am. Chem. Soc.* **1982**, *104*, 2571. (d) Mitchell, R. H.; Yan, J. S. H.; Dingle, T. W. *J. Am. Chem. Soc.* **1982**, *104*, 2551.

(3) Lai, Y. H.; Chen, P.; Peck, T.-G. *Pure Appl. Chem.* **1993**, *65*, 81.

(4) (a) Mitchell, R. H.; Iyer, Y. S.; Khalifa, M.; Mahadevan, R.; Venugopalan, S.; Weerawarna, S.; Zhou, P. *J. Am. Chem. Soc.* **1995**, *117*, 1514. (b) Mitchell, R. H.; Lau, D. Y. K. *Tetrahedron Lett.* **1995**, *36*, 9281.

(5) (a) Phillips, J. B.; Molyneux, R. J.; Sturm, E.; Boekelheide, V. *J. Am. Chem. Soc.* **1967**, *89*, 1704. (b) Lai, Y.-H.; Jiang, J. J. *J. Org. Chem.* **1979**, *44*, 4733. (c) Mitchell, R. H. In *Advances in Theoretically Interesting Molecules*; Halton, B., Ed.; JAI Press: Stanford, CT, 1989; Vol. 1, p 135.

(6) Mitchell, R. H.; Iyer, Y.S.; Mahadevan, R.; Venugopalan, S.; Zhou, P. *J. Org. Chem.* **1996**, *61*, 5116.

Figure 1. Compound sheet.

Benzannelation (as in **5**−**7**) (Figure 1) reduces the diatropicity in the macrocycle because of bond localization, whereas fusion with conjugated carbocycles (such as in **8** and **9**) does not significantly alter the ring

**Figure 2.** [12]Annulenium monocations and oxonium–annulenium dications from DMDHP and its derivatives.

current.[4] Substitution in **1** exerts a minor influence on the ring-current effects.[5] Unlike **1**, which isomerizes

readily, [2.2]metacyclophane monoenes with internal methyls (i.e., **10** and **11**) are kinetically stable, and their chemistry is just beginning to unravel.[7] Instead of the expected addition to the alkene double bond, dihydropyrene was rapidly formed on addition of bromine.[7] Metal π-complexation, however, allowed bromination at the alkene double bond.[7]

In parent **3**, electrophilic attack is directed to C-2/C-7 positions, and ipso attack occurs in superacids when these sites are substituted.[8] This led to the generation of several [12]annulenium monocations (see Figure 2).[8] With the formyl derivative (**12**) and with the cyclohexenone- and cyclopentenone-fused DMDHP (**8** and **9**), persistent oxonium–annulenium dications were generated (Figure 2), and their tropicities were examined via NMR.[9] Whereas the 16π-dianion of parent DMDHP is a textbook example of ring-current effects in action,[10] a persistent 12π-oxidation dication remains elusive.[11]

We report here on remarkably facile generation of dications: **14**[2+] and **15**[2+] (Scheme 1) from **10** and **11** and the first generation of both the protonation dication

Scheme 1. Formation of Diprotonated Dications from 10, 11, 13, and 6 and Oxidation Dication from 6
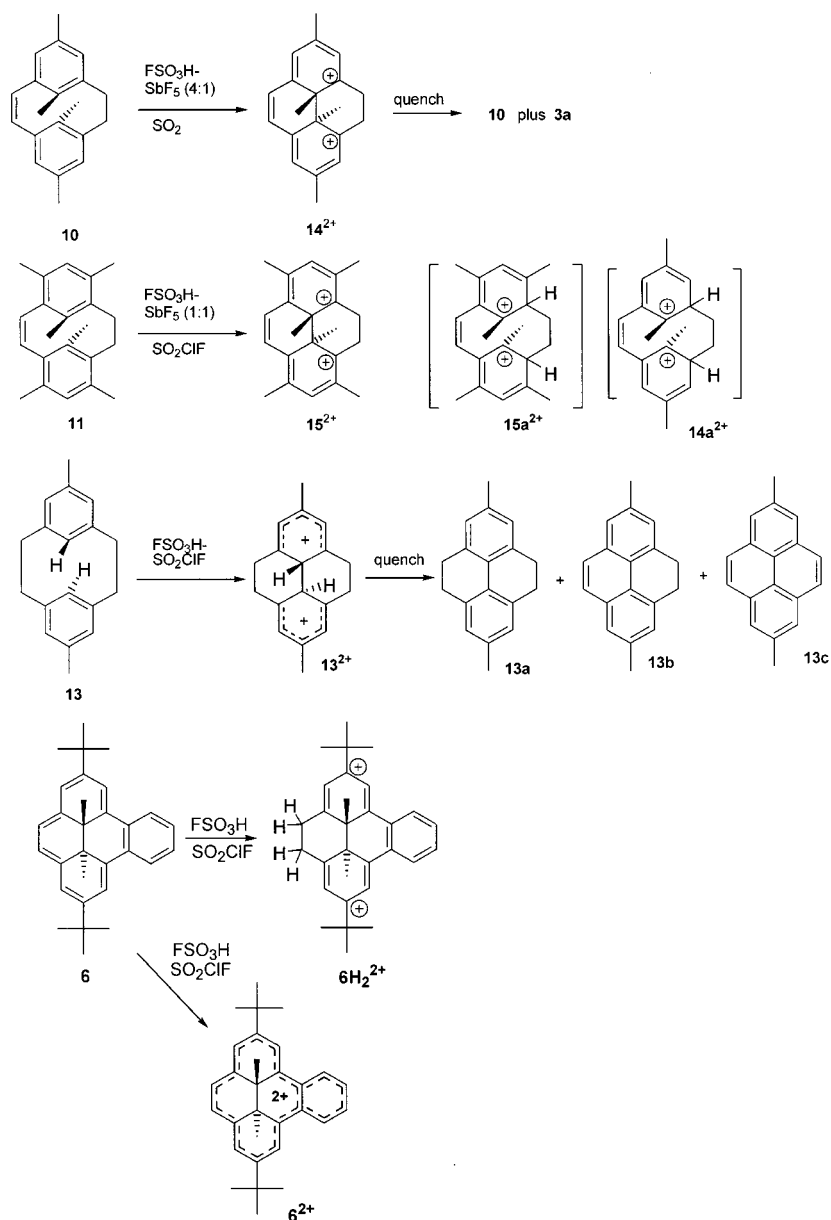
(**6**H_2^{2+}) and the oxidation dication (**6**$^{2+}$) from the 2,7-di-*tert*-butyl-substituted benz[*e*]annelated **6** under surprisingly mild conditions at low temperature in superacid media. Charge delocalization mode and tropicity in the resulting dications are gauged via NMR studies at 500 MHz. The outcome of protonation of 5,13-dimethyl-*anti*-[2.2]metacyclophane (**13**) is also reported.
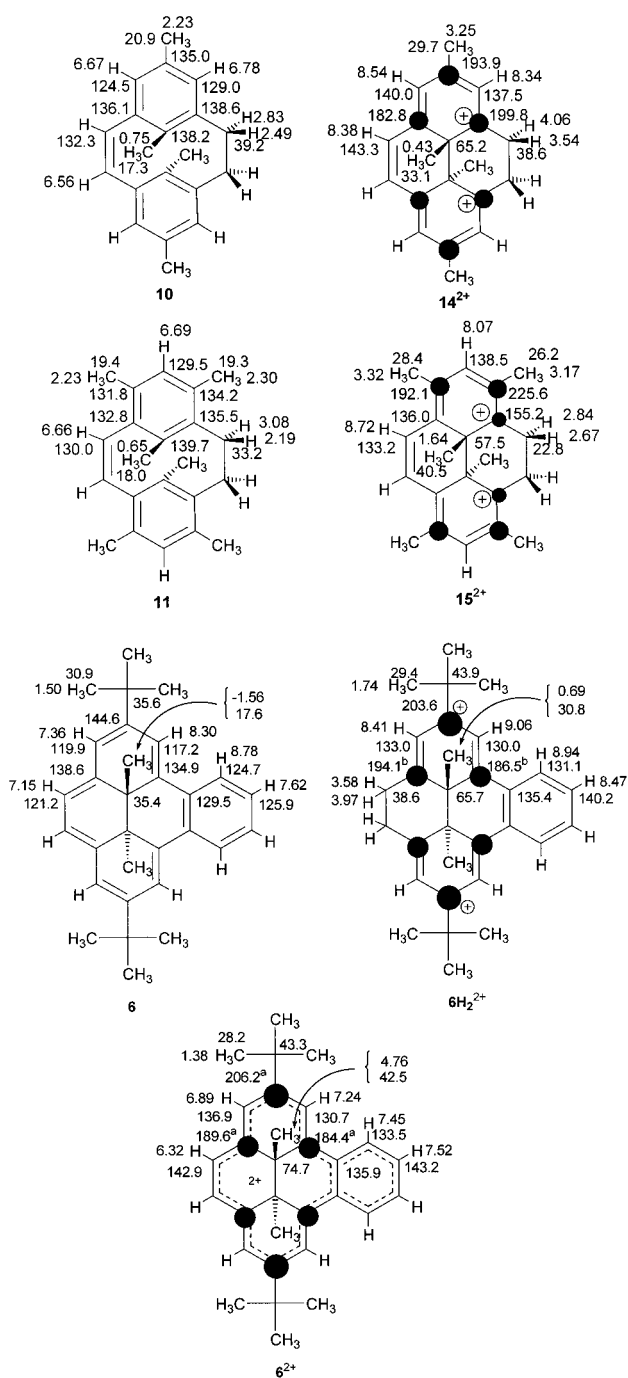
Results and Discussion

Stable Ion Studies of Cyclophane Monoenes 10 and 11 and [2.2]Metacyclophane 13. Reaction of **10** with FSO$_3$H·SbF$_5$ (4:1)/SO$_2$ at dry ice/acetone temperature gave a clear red solution whose NMR spectral data are fully consistent with near quantitative formation of **14**$^{2+}$ (Scheme 1 and Figure 3). Its ^{1}H NMR spectrum is a "deshielded version" of the monoene precursor, whereby the center of gravity of the three macrocycle ring proton singlets move from δ 6.67 in **10** to δ 8.42 in the dication. The internal methyls appear at δ 0.43, with the other methyl moving from δ 2.23 in **10** to δ 3.25 in **14**$^{2+}$. Relative NMR assignments for the C-4/C-5 methylene protons are unambiguous because the pseudoaxial protons (δ 3.54) gave NOE with the internal methyls, whereas the pseudoequatorial ones (δ 4.06) exhibited NOE with the H-3 ring protons (δ 8.34). The characteristic quaternary carbon bearing the internal methyl is at δ 65.2 in the ^{13}C NMR.

Positive charge is highly localized into the two cyclohexadienyl rings giving remarkably large Δδ^{13}C values for C-2/C-7, C-3a/C-6a, and C-8a/C-10a (Δδ between 61 and 47 ppm). The sample was practically unchanged when stored for 1 week at dry ice/acetone temperature. Quenching gave a 3:1 mixture of **10** and **3a**. Dication **14**$^{2+}$ was also cleanly generated in FSO$_3$H·SbF$_5$ (4:1)/SO$_2$ (essentially the same spectra; studied at −50 °C). Protonation with FSO$_3$H·SbF$_5$ (1:1)/SO$_2$ClF was less selective; it gave a dark-orange solution consisting of 90% **14**$^{2+}$ and 10% side products.[12]

Low-temperature reaction of **11** with FSO$_3$H·SbF$_5$ (1:1)/SO$_2$ClF gave a dark red-orange solution whose NMR spectral data are best interpreted as **15**$^{2+}$ (90%).[12] The distinction between **15**$^{2+}$ and the uncyclized version **15a**$^{2+}$ (shown in Scheme 1), based on the combined NMR data, had to rely on the fact that the δ 57.5 resonance bears no hydrogen (HMQC).[13] The center of gravity of two macrocycle ring proton singlets moves from δ 6.67 in **11** to δ 8.39 in the dication, and the internal methyls appear at δ 1.64. Relative NMR assignments for the C-4/C-5 methylene protons are based on NOE and are unambiguous.

A noteworthy feature is the observed differences in the chemical shifts of the ethano bridge and of the internal

(7) Mitchell, R. H.; Zhang, L. *J. Org. Chem.* **1999**, *64*, 7140.

(8) Laali, K. K.; Bolvig, S.; Raeker, T. J.; Mitchell, R. H. *J. Chem. Soc., Perkin Trans. 2* **1996**, 2635.

(9) Laali, K. K.; Tanaka, M.; Mitchell, R. H.; Lau, D. Y. K. *J. Org. Chem.* **1998**, *63*, 3059.

(10) Günther, H. *NMR Spectroscopy*, 2nd ed.; Wiley: New York, 1995; p 91.

(11) There is NMR evidence that the 2,7-dinitro-DMDHP is doubly ipso protonated, but the assignment was tentative (see ref 9).

(12) (a) These charged side products exhibited very low field aromatic signals at δ 10.70 (d), 10.50 (t), 9.66 (d), and 8.94 (d). (b) Local overheating in the higher acidity superacid could be responsible for side product formation.

(13) To get to **16a**$^{2+}$, just switch δ 155.2 and δ 57.5 in Figure 3 and remove the transannular bond and the ipso double protonate at the ethano bridge.

Figure 3. Complete ^{1}H and ^{13}C NMR assignments for **10**, **14**$^{2+}$; **11**, **15**$^{2+}$; and **6**, **6**H_2^{2+}, and **6**$^{2+}$.

methyls for **14**$^{2+}$ and **15**$^{2+}$. They also differ in their charge-delocalization mode, since in **15**$^{2+}$ the charge is highly localized on the four methyl-bearing macrocycle ring carbons (1, 3, 6, and 8) and to some extent at C-3a/C-8a. Dication **15**$^{2+}$ remained persistent when stored for 1 week at −75 °C.

For comparison, low-temperature protonation of *anti*-**13** was examined in several superacid media. With FSO$_3$H·SbF$_5$ (1:1)/SO$_2$ClF and FSO$_3$H·SbF$_5$ (4:1)/SO$_2$ClF, selectivity was poor, resulting in complex mixtures. Optimal selectivity was reached in FSO$_3$H/SO$_2$ClF. NMR data support the presence of a ring-closed symmetrical dication, most likely **13**$^{2+}$, as a major component in a mixture [aromatic singlet at δ 7.35 and internal hydro-

gens as a broad singlet at δ 3.60; corroboratory ^{13}C NMR evidence, in particular low field resonances at δ 228.3 (C), 174.2 (C), and 132.1 (CH)]. Quenching gave a mixture of 2,7-dimethyl-4,5,9,10-tetrahydropyrene (**13a**); 2,7-dimethyl-4,5-dihydropyrene (**13b**); and 2,7-dimethylpyrene (**13c**) in variable amounts in different reactions but with **13a** always predominating.[14]

Stable Ion Study of the [e]-Ring Benzannelated Derivative 6 and Comparison with 5. Annulene **6** reacted with FSO_3H/SO_2ClF at dry ice/acetone temperature to produce a dark-red solution whose NMR spectral data are fully consistent with the formation of the symmetrical diprotonation dication $6H_2{}^{2+}$ as the major component (ca. 90%),[15a] with double protonation occurring at the adjacent C-4/C-5 positions (Scheme 1, Figure 3). Relative NMR assignments for the C-4/C-5 methylene protons is unambiguous because the pseudoaxial protons gave NOE with the internal methyls, whereas the pseudoequatorial ones exhibited NOE with the H-3 ring protons. The internal methyls move from -1.56 ppm in the precursor to 0.69 ppm in $6H_2{}^{2+}$ and show deshielded ring protons (at δ 9.06 and 8.41) (Figure 3). Positive charge is highly localized into the two cyclohexadienyl rings, giving remarkably large $\Delta\delta{}^{13}$C values for C-2/C-7, C-3a/C-5a, and C-8a/C-12b carbons (between 68 and 40 ppm), with relatively minor delocalization into the annelated [e]-ring. Storing the sample at dry ice/acetone temperature led to the formation of 6^{2+} at the expense of $6H_2{}^{2+}$, such that their ratio reached 4:1 after 1 week.[15b]

The two-electron oxidation dication 6^{2+} exhibits three shielded annulene proton singlets with strongly deshielded internal methyls (by 6.32 ppm) (Figure 3). The charge delocalization mode in 6^{2+} and $6H_2{}^{2+}$ is rather similar, with the three carbon resonances due to C-2/C-7, C-3a/C-5a, and C-8a/C-12a being the most deshielded. Quenching of 6^{2+} returned the skeletally intact **6**. Interestingly, protonation of the unsubstituted benz[e]annelated derivative **5** under a similar set of conditions gave a mixture of at least three monoprotonated [12]annulenium cations (a green solution) with no evidence for diprotonation or dication formation.

Mechanistic Insight. The hitherto unknown 10π-dications 14^{2+} and 15^{2+} were generated from methylated [2.2]metacyclophane monoenes **10** and **11** and characterized by NMR. These *anti*-dimethyldihydroethanophenanthrenium dications are equivalent to C-4/C-5 diprotonated *trans*-dimethyldihydropyrenes. A process involving ene protonation, transannular ring closure, and oxidation (loss of hydride) is envisioned for their formation. Alternatively, doubly ipso-protonated dications $15a^{2+}$ and $14a^{2+}$ (Scheme 1) may be the initially formed species that rapidly convert to 14^{2+} and 15^{2+} by oxidation (H_2 loss) and transannular bond formation. Initial formation of

$15a^{2+}$ is especially appealing since the methyls are in the correct position to stabilize the charge.[16,17]

Under surprisingly mild conditions, the [e]-ring benzannelated derivative of Boekelheide's DMDHP is diprotonated at the adjacent C-4/C-5 positions to give $6H_2{}^{2+}$ and subsequently undergoes slow two-electron oxidation to give 6^{2+}. The observed double protonation ($6H_2{}^{2+}$) on adjacent positions (C-4/C-5) in the DMDHP skeleton is unprecedented. Dication $6H_2{}^{2+}$ may be viewed as a dimethyldihydrotriphenylene dication with an ethano bridge and represents a benzannelated analogue of 14^{2+}. Although the direction of shielding and deshielding in 6^{2+} is similar to the dianion 3^{2-}, its magnitude is significantly less.

Mode of benzannelation coupled to the inductively stabilizing effect of the Bu^t groups appear to have a significant influence on the ability of the annulene core to become doubly charged (via diprotonation or two-electron oxidation), since **5** behaved very differently under the same set of conditions. A significant feature is reversal of the ring-current effects between the 14π- ($4n + 2$) dication, $6H_2{}^{2+}$, and the 16π- ($4n$) oxidation dication, 6^{2+}.

Experimental Section

The [2.2]metacyclophane monoenes and benzannelated dimethyldihydropyrenes were available from previous studies (in R.H.M.'s laboratory).[2,18] FSO_3H (Allied and Aldrich) and SbF_5 (Fluorochem and Aldrich) were distilled in an all-glass distillation unit under a dry nitrogen atmosphere and stored in Nalgene bottles with Teflon caps. Standard procedures were used for the preparation of superacid solutions and for synthesis and purification of SO_2ClF.[19]

NMR spectra were recorded at 500 MHz between -70 and -50 °C. Complete assignments were achieved using ^{1}H, ^{13}C, H/H COSY, HMQC, and HMBC aided by NOED spectra.

General Procedure for Stable Ion Generation. SO_2ClF (ca. 0.4 mL) was distilled into a 5-mm NMR tube containing the substrate (10 mg) cooled to dry ice/acetone temperature. To the resulting cold suspension, precooled superacid was carefully added (2–3 drops) with efficient (vortex) mixing. Then 2 drops of cold CD_2Cl_2 was added on top of the solution, and the mixture was thoroughly mixed until homogeneous.

Quenching Experiments. The superacid solution was carefully poured into ice/bicarbonate, and the mixture was extracted with CH_2Cl_2. The organic layer was washed (10% NaCl) and dried ($MgSO_4$). The solvent was removed under reduced pressure, and the residue was analyzed by NMR.

Supporting Information Available: ^{1}H NMR and ^{13}C NMR spectra for 14^{2+}; H/H COSY and ^{13}C NMR spectra for $6H_2{}^{2+}$; and ^{1}H and ^{13}C NMR spectra for 6^{2+}. This material is available free of charge via the Internet at http://pubs.acs.org.

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(14) (a) Maxfield, M.; Bloch, A. N.; Cowan, D. O. *J. Org. Chem.* **1985**, *50*, 1789. (b) Mehta, G.; Shah, S. R. *Indian J. Chem.* **1990**, *29B*, 101. (c) Reynders, P.; Kuhnle, W.; Zachariasse, K. A. *J. Am. Chem. Soc.* **1990**, *112*, 3929.

(15) (a) Unidentified byproducts account for the remaining ~10%. (b) Formation of $6H_2{}^{2+}$ and 6^{2+} are envisaged in the following way:

$$6 \rightleftharpoons 6H_2{}^{2+} \text{ (fast)}$$
$$\downarrow$$
$$6^{2+} \text{ (slow)}$$
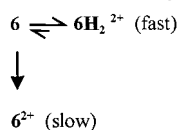
[formation of 6^{2+} is a slower process whose contribution to the mixture increases over time at the expense of $6H_2{}^{2+}$; competing oxidation is probably due to minor equilibrium formation of **6** on prolonged storage].

(16) AM1 predicts however that $10{\rightarrow}14^{2+}$ and $11{\rightarrow}15^{2+}$ conversions have lower $\Delta\Delta H_f$ than the corresponding $10{\rightarrow}14a^{2+}$ and $11{\rightarrow}15a^{2+}$ conversions.

(17) One of the reviewers suggested an alternative mechanism for consideration involving initial "hydride abstraction" at the ethano bridge, followed by transannular cyclization and protonation. Although there is precedent for generation of certain carbocations by hydride abstraction (i.e., trityl and tropylium using NO^+ salts; see, for example: Olah, G. A.; Laali, K. K.; Wang, X.; Prakash, G. K. S. *Onium Ions*; Wiley: New York, 1998; p 42), it is difficult to visualize hydride abstraction here as the "first step" for reactive substrates, such as **10** and **11**, in protic superacids (instead of initial rapid protonation).

(18) (a) Mitchell, R. H.; Ward, T. R.; Wang, Y.; Dibble, P. W. *J. Am. Chem. Soc.* **1999**, *121*, 2601. (b) Mitchell, R. H.; Ward, T. R. *Tetrahedron* **2001**, *57*, 3689.

(19) Laali, K. K.; Okazaki, T.; Coombs, M. M. *J. Org. Chem.* **2000**, *65*, 7399.