

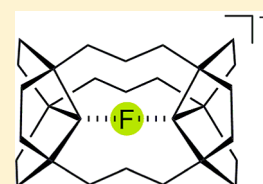
Extraordinary Modes of Bonding Enabled by the Triquinane Framework

Gorkem Gunbas and Mark Mascal*

Department of Chemistry, University of California Davis, 1 Shields Avenue, Davis, California 95818, United States

S Supporting Information

ABSTRACT: Incorporation of triquinane ring systems into a macrobicyclic framework enables the stabilization of unusual bonding arrangements, including 3-center-2-electron cation, 3-center-3-electron radical, and 3-center-4-electron anion systems, linear divalent fluorine, triplet carbenes, record short C–C bonds, a powerful proton sponge effect, and oxadionium (R_4O^{2+}) ions. The means to stabilize and conceivably isolate such species derives from the rigid, convex nature of the triquinane ring system, as well as the substitution of positions adjacent to the bridgehead atoms which would otherwise be vulnerable to elimination. The potential realization of hitherto undescribed bonding outcomes makes these macrocycles provocative synthetic targets.



INTRODUCTION

The engineering of circumstances under which otherwise fugitive chemical species can be freely observed has often been a matter of scientific preoccupation. In many such cases, the front-line approach is the application of steric bulk to impede ordinary reaction pathways, and a variety of structural and electronic curiosities have been isolated in this manner. Common examples include the steric shielding of strained cage hydrocarbons,¹ polyradicals,² and carbon networks³ with *tert*-butyl groups and the use of bulky ligands to kinetically stabilize multiple bonding,^{4,5} small rings,⁶ or low coordination states (radicals and carbene analogues)⁷ in the heavier main group elements. Purely geometric constraints can also be used to achieve unnatural bond configurations, for example in the quest for planar tetracoordinate carbon.⁸ Yet another approach involves the spatial confinement and chemical isolation of reactive intermediates within container molecules. Perhaps the most famous platform of this description is that of the carcerands, originally developed by Cram and co-workers in the 1980s, which were used to trap such elusive species as cyclobutadiene and benzyne.⁹

The macrobicyclic effect has been used with remarkable success to produce complexes of a variety of chemical species via metal–ligand bonding and/or noncovalent interactions. In his classic review on intrabridgehead chemistry, Alder showed how conformational constraints in macrobicycles could also be applied to the study of orbital combinations, such as 2-center-4-electron (antibonding), 2-center-2-electron (bonding or frustrated, subject to overlap), and 3-center-2-electron systems (Figure 1).¹⁰ 3-Center bonding motifs with other electronic configurations may also be of interest, the character of which depends on the atomic center included between the bridgeheads.

In this work, we take the macrobicyclic effect to a new level, in the form of a molecular scaffold wherein two triquinane ring systems are linked to form what may be likened to an atomic-scale diamond anvil. A diamond anvil is composed of two

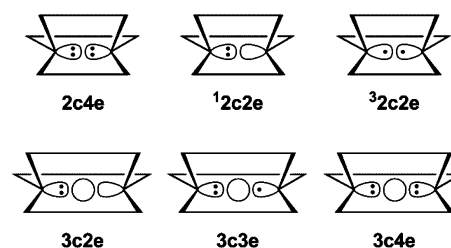


Figure 1. Examples of transannular bonding motifs.

single-crystal diamonds with opposing tips which are forced together in a device to generate high pressures.¹¹ The culet of the diamond, or point where the facets of the pavilion meet, corresponds here to the vertex of the three five-membered rings, and the “pressure” is controlled by the length of the tethers (Figure 2). In effect, the bonding arrangement in Figure

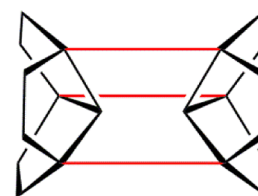


Figure 2. Conceptual representation of a molecular diamond anvil based on the triquinane framework.

2 can also be viewed as a forced “in–in” cryptand, since the apical atom of a triquinane cannot be inverted, unlike in ordinary cryptands which, depending on their structure, may exist as “in–in”, “in–out”, and “out–out” isomers with respect to the configuration at the bridgehead atoms.¹² From a molecular perspective, the environment within the cage is of

Received: August 5, 2013

Published: September 6, 2013

interest not only in the sense that the apexes can be forced together, but also held apart from each other.

We have promoted the rigid, convex triquinane ring system as a platform for proton chelates,¹³ tripodal ligands,¹⁴ fullerene complexation,^{15,16} surfactant headgroups,¹⁷ ultrastable alkyloxonium salts,¹⁸ aromatic $C_{20-n}X_n$ fullerene fragments,^{19,20} and the generation of record C–O bond lengths.^{21,22} Here, we theoretically recruit it into new roles using the concept illustrated in Figure 2, as described below.

METHODS

Computational modeling was carried out at the second-order Møller–Plesset/6-31+G(d,p) level of theory using either the Gaussian03 or Gaussian09 program,²³ with all structures confirmed as energy minima (or transition states, where noted) by vibrational analysis at the density functional B3LYP/6-31+G(d,p) level of theory. Default methods and SCF convergence criteria were applied. Calculations were expedited by making use of C_3 or D_3 symmetry in the structures where possible. Natural Bond Orbital (NBO) analysis was performed as implemented in Gaussian09 using NBO version 3.

RESULTS AND DISCUSSION

Symmetric [C...X...C] Bonding. 3-Center-2-electron (3c2e) bonding is a relatively common observation in organometallic and inorganic chemistry, for example, in boron hydrides, bridged metal halides, bridged metal alkyls, and agostic interactions.²⁴ However, stable examples of collinear 3c2e bonding in organic chemistry are rare.²⁵ The archetypal example of the single-potential, 3c2e bond is that of the bicyclo[4.4.4]tetradecyl-1-cation **2** (Figure 3), which is observable under ambient conditions in acid solution.²⁶ An

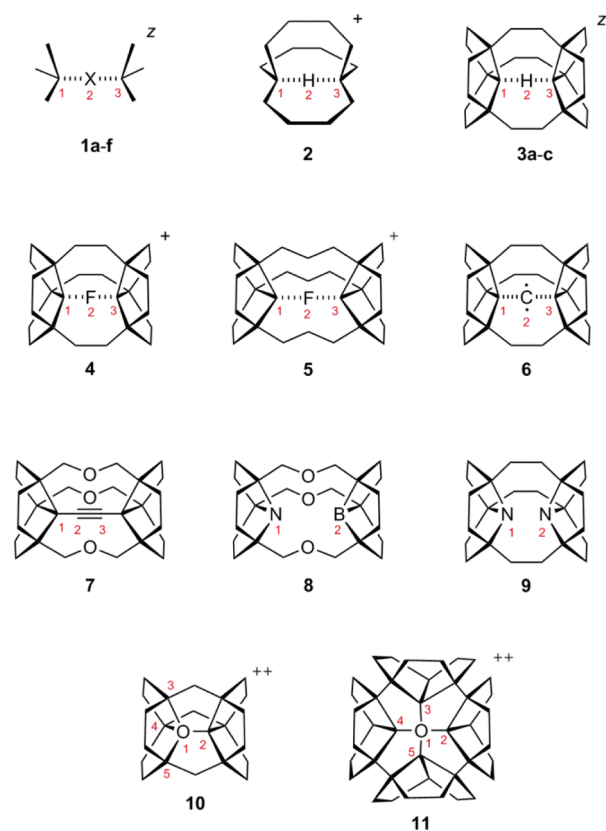


Figure 3. Triquinane-based macrobicyclic systems which demonstrate unconventional transannular bonding.

analogous system incorporating triquinane rings (**3a**, $z = 1$) can be conceptualized, and modeling shows that the C–H–C bond distances in **3a** are consistent with those in **2** computed at the same level of theory (Table 1).²⁷ The *ad libitum* C–H–C

Table 1. Distances (Å) Computed at the MP2/6-31+G(d,p) Level of Theory

	point group	1...2	2...3	1...3
1a , X = H, $z = 1$	C_3	1.255	1.255	2.509
1b , ^a X = H, $z = 0$	D_3	1.331	1.331	2.663
1c , ^a X = H, $z = -1$	D_3	1.432	1.432	2.863
1d , ^a X = F, $z = 1$	D_3	1.698	1.698	3.396
1e , X = C, $z = 0$	C_3	1.478	1.478	2.955
1f , X = C_{2v} , $z = 0$	D_3	1.470	1.229	
2	C_3	1.232	1.232	2.464
3a , $z = 1$	C_3	1.228	1.245	2.474
3b , $z = 0$	C_3	1.118	1.520	2.639
3c , $z = -1$	C_3	1.183	1.507	2.690
4	C_3	1.500	1.501	3.001
5	C_3	1.451	2.386	3.837
6	C_3	1.371	1.373	2.745
7	C_3	1.362	1.183	
8	C_3	3.604		
9	C_3	2.696		
10	C_3	1.531		1.642
11	C_3	1.569		1.569

^aStationary point that is not an energy minimum.

distances in the nonmacrocyclic model **1a** (X = H, $z = 1$) are only slightly greater than those in **3a**, indicating that little intramolecular pressure is being applied. While **2** is prone to β -elimination, **3a** would be expected to be robust and should even be isolable with the appropriate counterion.

Unlike **1a**, the analogous 3- or 4-electron systems **1b** (X = H, $z = 0$) and **1c** (X = H, $z = -1$) dissociate, giving isobutane plus the *tert*-butyl radical and *tert*-butyl anion, respectively. Minimization of **1b** and **1c** in the D_3 point group leads to transition state structures with somewhat longer C–H–C bond distances than in **1a** (Table 1). Corresponding macrobicycles **3b** ($z = 0$) and **3c** ($z = -1$) have asymmetric minima, with the hydrogen closer to one of the bridgeheads, as anticipated by the results with **1b** and **1c**. However, transition state searches in both cases generate symmetric structures with energies <2 kcal mol⁻¹ from the minima, such that these systems might be best represented by exchange-averaged D_3 symmetric complexes.

The corresponding divalent fluorine model compound **1d** (X = F, $z = 1$) with a 180 °C–F–C bond angle would not be predicted to be a minimum energy structure due to the expectation of a bent configuration at fluorine, such as is observed in Me_2F^+ ,²⁸ and in the recently reported fluoronium intermediate of Struble et al., in which anchimeric assistance from covalent fluorine in a sesquiorbornane framework was demonstrated in an S_N1 reaction.²⁹ Indeed, if C_3 symmetry is forced on the system, **1d** dissociates into *tert*-butyl fluoride and the *tert*-butyl cation. Imposing D_3 symmetry results in a structure with three imaginary vibrational frequencies; one in which the F vibrates along the principle symmetry axis and two C–F–C bends in directions normal to the axis. Remarkably, however, the fluorine complex **4** has no imaginary frequencies. The C–F bond distances are essentially equal at 1.50 Å, which is slightly shorter than in Me_2F^+ (1.54 Å) but longer than the covalent C–F bond in tertiary alkyl fluorides (avg 1.42 Å).³⁰

NBO localization of the molecular orbitals fits the fluorine in **4** to the intuitive sp hybrid formalism.³¹ Optimization in a more spacious cavity (*viz.* **5**) led to the bonding of the F to one of the bridgehead carbons (C1–F distance 1.45 Å, bond angles around C1 avg 109.5°), with the other bridgehead carbon bearing the positive charge (bond angles around C3 116.5°). However, modeling identifies a transition state with the fluorine at the midpoint of the cavity, 1.78 Å from each bridgehead, with an energy only 9.0 kcal mol⁻¹ above the minimum. As above, such a low barrier indicates an exchange-averaged symmetric structure at ambient temperatures. McMurry called the stabilization of divalent fluorine “the ultimate goal of many physical organic chemists over the past half century.”²⁴ Here, the prospect of not only stabilizing the divalent fluorine but also describing a new geometry/bonding character in R_2F^+ species is highly intriguing.

Another attractive “guest” for the triquinane-based macrobicyclic system is neutral divalent carbon which, when constrained to a linear geometry, should occur in a triplet diradical state. It has only been in recent times that the first examples of persistent triplet carbenes have been reported.^{32,33} In all cases, the diradical center is attached to aromatic rings, which enables extensive spin delocalization, leading to species with half-lives on the order of days in some cases.³⁴ Unrestricted optimization of compound **6** as a triplet results in a minimum energy structure with no wave function instability. The macrobicyclic environment in which this carbene is confined forces an uncharacteristic linear geometry around the divalent carbon and gives rise to unusually short C–C: bonds (1.37 Å). The C–C:–C angle in triplet dimethyl carbene is 130.4° and the C–C: distance is 1.48 Å.³⁵ In triplet *di-tert*-butyl carbene **1e** the angle widens to 138.3° but the C–C: bonds are little changed (1.49 Å). Even given that the C–C: bond is generally shorter than a typical C–C bond, the degree of bond compression in **6** is substantial, at 0.063 Å shorter than the current record-holder (1.436 Å).³⁶ Although other theoretical studies have proposed C–C bonds as short as 1.31 Å in 3-fold-bridged tetrahedryltetrahedranes,³⁷ such dramatic results come at the expense of stretching other bonds to unrealistic values. While the ethylene bridges in **6** show some degree of C–C bond lengthening (up to 1.58 Å), this would not preclude the existence of this molecule.

Related to the above system is the case where a C_2 fragment is squeezed between two triquinane vertexes (**7**). The purpose here is to further probe the compressibility of the $C_{sp}-C_{sp3}$ bond, which is 1.47 Å long in the acyclic model **1f**. With the appropriate bridging chains, the intrabridgehead C–C single bond distances are reduced to 1.36 Å, slightly less even than in **6**, while the $C\equiv C$ bond is little affected. As with **6**, the bridges between the triquinane rings in **7** show some evidence of bond and angle distortion, but nothing of serious concern.

Frustrated Lewis Pairs and Filled Orbital Interactions.

Situations where Lewis acidic and Lewis basic sites, often in the same molecule, are sterically prevented from either intra- or intermolecularly “neutralizing” each other are rapidly becoming important as metal-free catalysts for the hydrogenation of polar double bonds as well as other reactions.³⁸ Geometry optimization of **8** starting with a B–N bond at a standard R_3B-NR_3 distance (1.69 Å)³⁹ terminates at an energy-minimized structure with the bridgehead atoms separated by 3.60 Å. The puckered nature of the triquinane system also forces a reactive pyramidal geometry at boron.⁴⁰ Although **8** cannot split hydrogen due to the proximity of the B and N, it

could potentially host a transition metal via unusual metal-borane complexation (**12**) (Figure 4). Examples of Co,⁴¹ Ni,⁴¹

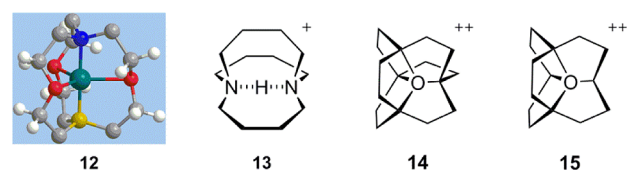


Figure 4. **12:** model of N–M–B bonding in **8** with the triquinane ring frameworks removed for clarity.

and Cu⁴² complexes with M–B bonds in a trigonal bipyramidal coordination geometry have been described. The nature of metal–boron bonding has been discussed in detail.⁴³

The antithesis of a frustrated system is when two Lewis bases are forced into each other’s van der Waals space. This forcing together of nonbonding electron pairs on nitrogen has been the basis of the “proton sponge” effect, around which has grown a family of “superbasic” polyamines.⁴⁴ The question becomes how close two nitrogens can get, or indeed how basic a proton sponge can become. This will depend to an extent on the relative orientation of the lone pairs. In **9**, they are aligned to the C_3 axis of the molecule and only 2.70 Å apart (vs 3.22 Å sum of the vdW radii).⁴⁵ **9** can be recognized as an azatriquinane-based version of Alder’s 1,6-diazabicyclo[4.4.4]-tetradecane **13** which, when protonated, gives the shortest known N–H–N hydrogen bond (N–N distance 2.53 Å in the crystal structure).⁴⁶ Gas-phase modeling of $13H^+$ starting from the crystal coordinates reproduces the structure almost exactly, with an N–N distance of 2.54 Å. The corresponding distance in $9H^+$ is virtually identical (2.53 Å). However, calculation of the respective protonation energies of **9** and **13** shows that **9** is more basic than **13** on the order of 9.7 kcal mol⁻¹, correlating to a difference of about 3.5 pK_a units in acetonitrile.⁴⁷ This can be explained both by the somewhat closer approach of the two nitrogens in **9** in the free base state (2.70 Å, vs 2.76 Å in **13**) and the fact that azatriquinane itself is among the most basic trialkyl amines known, the conjugate acid of which has a pK_a value ca. 0.5 pK_a units greater than that of quinuclidine.⁴⁸

Tetravalent Chalcogen Cages. Putting oxygen at the apical junction of four triquinane ring systems, as in **14**, results in an oxadionium (R_4O^{2+}) species that has been predicted to be thermodynamically stable.^{49,50} We recently showed that oxatriquinanes could be protonated to give the R_3OH^{2+} species, but in the absence of a framework like that in **14** to hold the dication together, C–O bond fragmentation occurs to give a bicyclic oxonium-carbenium cation pair.⁵¹ Even putting the O^{2+} center at the junction of two triquinanes (**15**) is not sufficient to stabilize the system, which reacts with solvent at one of the secondary α -carbons.⁵¹

Incorporating oxatriquinane into the macrobicyclic system **10**, which can be considered the “diamond anvil” analogue of **14**, essentially forces a carbocation at a triquinane apex to squat over the oxatriquinane lone pair. The potential stability of such a structure can be evaluated by considering the modeled C–O bond distances. While the C–O bonds in **14** average 1.62 Å, in **10** the C–O bond between the bridgeheads is only 1.53 Å, which is not much longer than that of a typical oxonium ion, while the three other C–O bonds are 1.64 Å. Although this may appear very long for a C–O bond, we have recently characterized an oxatriquinane with a C–O bond length of 1.66 Å.²² Taking the concept to its extreme, putting oxygen at the

focal point between four interconnected triquinane rings gives **11**, which has the shortest yet mean C–O bond lengths calculated for an R_4O^{2+} species at 1.57 Å. With the oxygen sequestered away in the center of the nearly spherical **11** (see Figure 1 in Supporting Information), the stability of such a species would be difficult to question.

CONCLUSION

In summary, this work describes opportunities to stabilize heretofore marginally stable (C–H...C⁺, C–C:–C) or never before isolated (C–H...C[–], C–H...C[–], C–F...C⁺, R_4O^{2+}) species, as well as probing the boundaries of orbital frustration, C–C bond compression, and the proton sponge effect. The key structural advantages of triquinane-based macrobicycles over the simple bicyclo[4.4.4]tetradecyl ring system are the noninvertible nature and acute pyramidalization of the bridgehead atoms,⁵² as well as full substitution at the vulnerable carbons α to the bridgeheads within a rigid, tricyclic framework.

At this point, **3–11** remain purely theoretical and, although one can envisage possible scenarios for their synthesis, their practical accessibility is not addressed here. Like so many works on challenging molecules that have gone before the present contribution,⁵³ we leave this to the readers' initiative.

ASSOCIATED CONTENT

Supporting Information

Full citation for Gaussian03, full citation for Gaussian09, charges, multiplicities, and Cartesian coordinates for all calculations used in this work. This material is available free of charge via the Internet at <http://pubs.acs.org>.

AUTHOR INFORMATION

Corresponding Author

*E-mail: mjmascal@ucdavis.edu.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was financially supported by the National Science Foundation (Grant No. CHE-0957798). G.G. thanks the Turkish Higher Education Council for a scholarship.

REFERENCES

- (1) Maier, G.; Rang, H.; Born, D. In *Cage Hydrocarbons*; Olah, G. A., Ed.; Wiley: New York, 1990; pp 219–259.
- (2) Rajca, A. *Chem. Rev.* **1994**, *94*, 871–893.
- (3) Diederich, F.; Kivala, M. *Adv. Mater.* **2010**, *22*, 803–812.
- (4) Power, P. P. *Chem. Rev.* **1999**, *99*, 3463–3504.
- (5) Sasamori, T.; Tokitoh, N. *Dalton Trans.* **2008**, 1395–1408.
- (6) Driess, M.; Gruetzmacher, H. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 828–856.
- (7) Mizuhata, Y.; Sasamori, T.; Tokitoh, N. *Chem. Rev.* **2009**, *109*, 3479–3511.
- (8) (a) Rottger, D.; Erker, G. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 812–827. (b) Keese, R. *Chem. Rev.* **2006**, *106*, 4787–4808.
- (9) Warmuth, R. Carcerands and Hemicarcerands. In *Supramolecular Chemistry: From Molecules to Nanomaterials*; Gale, P. A.; Steed, J. W., Eds.; Wiley: New York, 2012; Vol. 3, pp 917–954.
- (10) Alder, R. W. *Tetrahedron* **1990**, *46*, 683–713.
- (11) Holzapfel, W. B.; Isaacs, N. S. *High-Pressure Techniques in Chemistry and Physics*; Oxford University Press: Oxford, 1997.
- (12) Alder, R. W.; East, S. P. *Chem. Rev.* **1996**, *96*, 2097–2112.

(13) Mascal, M.; Lera, M.; Blake, A. J.; Czaja, M.; Kozak, A.; Makowski, M.; Chmurzynski, L. *Angew. Chem., Int. Ed.* **2001**, *40*, 3696–3698.

(14) Jevric, M.; Zheng, T.; Meher, N. K.; Fettinger, J. C.; Mascal, M. *Angew. Chem., Int. Ed.* **2011**, *50*, 717–719.

(15) Pham, D.; Cerón Bertran, J.; Olmstead, M. M.; Mascal, M.; Balch, A. L. *Org. Lett.* **2005**, *7*, 2805–2808.

(16) Pham, D.; Cerón Bertran, J.; Olmstead, M. M.; Mascal, M.; Balch, A. L. *Cryst. Growth Des.* **2007**, *7*, 75–82.

(17) Baldelli, S.; Mascal, M.; Cerón Bertran, J. *Chem. Phys. Lett.* **2006**, *427*, 72–75.

(18) Mascal, M.; Hafezi, N.; Meher, N. K.; Fettinger, J. C. *J. Am. Chem. Soc.* **2008**, *130*, 13532–13533.

(19) Mascal, M.; Cerón Bertran, J. *J. Am. Chem. Soc.* **2005**, *127*, 1352–1353.

(20) Mascal, M. *J. Org. Chem.* **2007**, *72*, 4323–4327.

(21) Gunbas, G.; Hafezi, N.; Sheppard, W. L.; Olmstead, M. M.; Stoyanova, I. V.; Tham, F. S.; Meyer, M. P.; Mascal, M. *Nature Chem.* **2012**, *4*, 1018–1023.

(22) Gunbas, G.; Sheppard, W. L.; Fettinger, J. C.; Olmstead, M. M.; Mascal, M. *J. Am. Chem. Soc.* **2013**, *135*, 8173–8176.

(23) Gaussian, Inc., Wallingford, CT, 2004, 2009. Full Gaussian03 and Gaussian09 references are included in the Supporting Information.

(24) McMurry, J. E.; Lectka, T. *Acc. Chem. Res.* **1992**, *25*, 47–53.

(25) In passing, it can be noted that cyclic 3c2e systems have been described, for example, cyclopropenium cations and most recently the 2-norbornyl cation: Scholz, F.; Himmel, D.; Heinemann, F. W.; Schleyer, P. v. R.; Meyer, K.; Krossing, I. *Science* **2013**, *341*, 62–64.

(26) McMurry, J. E.; Lectka, T.; Hodge, C. N. *J. Am. Chem. Soc.* **1989**, *111*, 8867–8872.

(27) Note that the bonding in **2** has been comprehensively modeled: DuPre, D. B. *J. Phys. Chem. A* **2005**, *109*, 622–628.

(28) Jubert, A.; Okulik, N.; Michelini, M.; del, C.; Mota, C. J. A. *J. Phys. Chem. A* **2008**, *112*, 11468–11480.

(29) Struble, M. D.; Scerba, M. T.; Siegler, M.; Lectka, T. *Science* **2013**, *340*, 57–60.

(30) Statistics on 47 tertiary alkyl fluorides with $R < 0.1$ in the Cambridge Structural Database version 5.34 (November 2012). Data extracted using the Cambridge Structural Database System program MOGUL version 1.5.

(31) For a review of the use of natural bond orbitals, see: Weinhold, F.; Landis, C. R. *Chem. Educ. Res. Pract.* **2001**, *2*, 91–104.

(32) Tomioka, H.; Watanabe, T.; Hirai, K.; Furukawa, K.; Takui, T.; Itoh, K. *J. Am. Chem. Soc.* **1995**, *117*, 6376–6377.

(33) Tomioka, H.; Iwamoto, E.; Itakura, H.; Hirai, K. *Nature* **2001**, *412*, 626–628.

(34) Iwamoto, E.; Hirai, K.; Tomioka, H. *J. Am. Chem. Soc.* **2003**, *125*, 14664–14665.

(35) Matzinger, S.; Fülischer, M. P. *J. Phys. Chem.* **1995**, *99*, 10747–10751.

(36) Tanaka, M.; Sekiguchi, A. *Angew. Chem., Int. Ed.* **2005**, *44*, 5821–5823.

(37) Martínez-Guajardo, G.; Donald, K. J.; Wittmaack, B. K.; Vazquez, M. A.; Merino, G. *Org. Lett.* **2010**, *12*, 4058–4061.

(38) Review: Stephan, D. W.; Erker, G. *Angew. Chem., Int. Ed.* **2010**, *49*, 46–76.

(39) Bubnov, Y. N.; Gurskii, M. E.; Pershin, D. G.; Lyssenko, K. A.; Antipin, M. Y. *Russ. Chem. Bull.* **1998**, *47*, 1771–1777.

(40) The pyramidal geometry around boron in **8** raises the energy of the system about 15 kcal mol^{–1} (MP2/6-31+G**) above what it would be if the boron were able to adopt a planar geometry. This can be estimated by doing a partial optimization of Me₃B with C–B–C angles frozen at the value they have in **8** (112.8°) and comparing the energy to planar Me₃B minimized without constraints.

(41) Nuss, G.; Saischek, G.; Harum, B. N.; Volpe, M.; Gatterer, K.; Belaj, F.; Mosch-Zanetti, N. C. *Inorg. Chem.* **2011**, *50*, 1991–2001.

(42) Nuss, G.; Saischek, G.; Harum, B. N.; Volpe, M.; Belaj, F.; Mosch-Zanetti, N. C. *Inorg. Chem.* **2011**, *50*, 12632–12640.

(43) Parkin, G. *Organometallics* **2006**, *25*, 4744–4747.

(44) Review: Chambron, J.-C.; Meyer, M. *Chem. Soc. Rev.* **2009**, *38*, 1663–1673.

(45) Rowland, R. S.; Taylor, R. *J. Phys. Chem.* **1996**, *100*, 7384–7391.

(46) Alder, R. W.; Orpen, A. G.; Sessions, R. B. *J. Chem. Soc., Chem. Commun.* **1983**, 999–1000.

(47) After the linear relationship $\text{p}K_{\text{a}}(\text{theory}) = -0.357(\Delta E_{\text{prot}}) - 68.8$, derived by plotting ΔE_{prot} against experimental $\text{p}K_{\text{a}}$ values in acetonitrile for a range of amine bases at the HF/6-31G(d) level of theory; see ref 13.

(48) Hext, N. M.; Hansen, J.; Blake, A. J.; Hibbs, D. E.; Hursthouse, M. B.; Shishkin, O. V.; Mascal, M. *J. Org. Chem.* **1998**, *63*, 6016–6020.

(49) Schneider, T. F.; Werz, D. B. *Org. Lett.* **2010**, *12*, 772–775.

(50) A structural analogue of **14** with carbon at the center is known: Paquette, L. A.; Vazeux, M. *Tetrahedron Lett.* **1981**, *22*, 291–292.

(51) Stoyanov, E. S.; Gunbas, G.; Hafezi, N.; Mascal, M.; Stoyanova, I. V.; Tham, F. S.; Reed, C. A. *J. Am. Chem. Soc.* **2012**, *134*, 707–714.

(52) Modeled (MP2/6-31+G(d,p)) C–N–C angles for azatriquinane and triethylamine are 108.9° and 110.8°, respectively.

(53) Recent examples: (a) Wu, Y.-B.; Duan, Y.; Lu, G.; Lu, H.-G.; Yang, P.; Schleyer, P. v. R.; Merino, G.; Islas, R.; Wang, Z.-X. *Phys. Chem. Chem. Phys.* **2012**, *14*, 14760–14763. (b) Shakib, F. A.; Momeni, M. R.; Wu, J. I.; Schleyer, P. v. R.; Azizi, Z.; Ghambarian, M. *Org. Lett.* **2011**, *13*, 3600–3603. (c) Ito, K.; Pu, Z.; Li, Q.-S.; Schleyer, P. v. R. *Inorg. Chem.* **2008**, *47*, 10906–10910. (d) Pei, Y.; An, W.; Ito, K.; Schleyer, P. v. R.; Zeng, X. C. *J. Am. Chem. Soc.* **2008**, *130*, 10394–10400. (e) Wang, Z.-X.; Zhang, C.-G.; Chen, Z.; Schleyer, P. v. R. *Inorg. Chem.* **2008**, *47*, 1332–1336. (f) Islas, R.; Heine, T.; Ito, K.; Schleyer, P. v. R.; Merino, G. *J. Am. Chem. Soc.* **2007**, *129*, 14767–14774. (g) Ito, K.; Chen, Z.; Corminboeuf, C.; Wannere, C. S.; Zhang, X. H.; Li, Q. S.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **2007**, *129*, 1510–1511.