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The Effect of the Double Bond Pyramidalization on the Mode of the Bromination Reaction: Bromination of Benzobicyclononadiene

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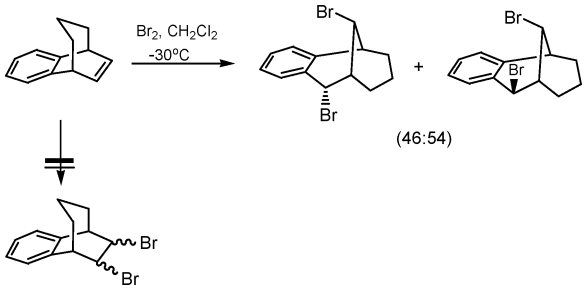
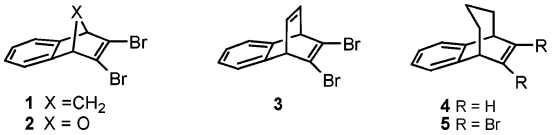


The bromination of 6,7,8,9-tetrahydro-5*H*-5,9-ethenobenzo[*a*][7]annulene yielded regio- and stereospecifically formed dibromides arising from the alkyl shift where the bromine exclusively attacks the double bond from the *endo* face of the double bond. DFT calculations on model compounds showed that the pyramidalization of the double bond and steric repulsion caused by the methylene protons are responsible for the stereo- and regioselective addition of bromine.

Introduction

Vinyl dibromides are suitable starting materials for trimerization reactions to give benzocyclotrimers, which are interesting compounds in view of the continuing subject of aromaticity[1] and because they represent fullerene substructures or even subunits of new, hitherto unobserved carbon allotropes.[2] Recently, we reported the trimerization of the following compounds **1**−**3**.[1g−i]



1 X =CH_2
2 X = O

3

4 R = H
5 R = Br

The vinyl bromides **1**−**3** were synthesized by addition of bromine to the double bond of the bicyclic olefins at high temperature, followed by HBr elimination. Repeating this reaction sequence resulted in the formation of the corresponding vinyl dibromides. In this work, we were particularly interested in the synthesis of **5**, which is suitable for the trimerization reaction. Though the addition of bromine to a carbon−carbon

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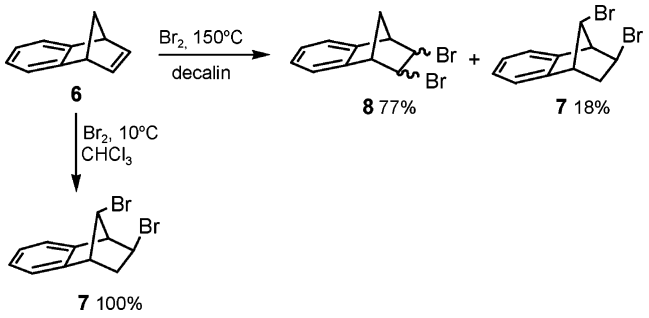
SCHEME 1



double bond using molecular bromine is one of the simplest reactions of unsaturated compounds,[3] the bromination of unsaturated bicyclic systems with molecular bromine generally leads to rearrangement of the molecular skeleton.[4]

In a previous report, we showed that bromination of benzonorbornadiene **6** at 10 °C gives only the rearranged product **7**. However, when the bromination reaction of this molecule is carried out at 150 °C, the non-rearranged isomeric products **8** were formed in 77% yield along with the rearranged product **7** (Scheme 1).[5] Besides the temperature,[6] the light,[7] concentration,[4g] neighboring group participation, and steric factors[3b,8] also affect the structures of products formed in the bromination reactions. In this paper, we will discuss the effect of the double bond pyramidalization on the outcome of the bromination reaction.

Results and Discussion

The starting material, 6,7,8,9-tetrahydro-5*H*-5,9-ethenobenzo[*a*][7]annulene (**4**), was synthesized using a procedure described in the literature[9] (Scheme 2). The adduct **10** was obtained from the Diels−Alder reaction of cyclohepta-1,3-diene (**9**) with 1,4-benzoquinone. Selective reduction of **10** with diisobutylaluminum hydride followed by reaction of the formed diol with phosphorus oxychloride in pyridine resulted in the formation of **4**.

The electrophilic addition of bromine to **4** was carried out in methylene chloride solution at −30 °C. The ^{1}H NMR spectral studies of the crude product revealed the formation of two isomeric rearranged products **11** and **12** in quantitative yield and in a ratio of 46:54. The mixture was separated by silica gel column chromatography. The dibromide **11** was isolated as the first fraction in 48% yield. We observed that compound **12** isomerizes to compound **11** by standing at room temperature as well as during column chromatography. The calculations (B3LYP/6-31G(d)) show that the isomer **11** is 1.685 kcal/mol more stable than the product **12**. Therefore, the major product **12** formed initially could not be isolated in a pure state. The spectral data for the isomer **12** were extracted from the NMR spectra of the **11**/**12** mixture. Furthermore, bromoalcohols **13** and **14** were isolated in 3 and 21% yields, respectively. Those alcohols were formed by hydrolysis of the benzylic bromides during column chromatography. Careful examination of the crude reaction mixture did not reveal the formation of even trace amount of the non-rearranged product **15**.

It is important to know the exact configurations of the bromine atoms in **11** and **12** for determining the mechanism of formation of these isomers. We mainly used the coupling constant between the bridge proton H_9 and the benzylic proton H_{10} to deduce the correct configuration of the bromine atoms and hydroxy groups at C_{10}. As a consequence of the rigid geometries and reliability of the Karplus rule[10] in [3.3.1]nonene, the dihedral relationship of the H_9 proton to H_{10exo} (40°) and to H_{10endo} (82° obtained from AM1 geometry optimization calculations) is sufficiently distinctive to be revealed by the magnitude of the spin−spin interaction. Thus, the high value of $J_{9,10}$ (J = 6.2 Hz) is only explained by the *endo* orientation of the bromine atom bonded to the C_{10} atom. There were no measurable coupling constants between the related protons in compounds **12** and **14**. The formation mechanism of the products requires the *syn* orientation of the bromine atom at C_{11}. The proposed structures of **11**, **12**, **13**, and **14** were also further supported by chemical transformations. For example, when a mixture of dibromides **11** and **12** was hydrolyzed with $CaCO_3/H_2O$ and the formed hydroxy bromide **14** further reacted with CrO_3, ketone **16** was formed in high yield (Scheme 3).

Since we were particularly interested in the formation of the non-rearranged products **15**, we performed bromine addition at temperatures from 0 to 150 °C. The mechanism of bromine addition at higher temperatures is different than the mechanism at low temperatures. We have already demonstrated that at high temperatures bromine radicals are involved.[5] Since the radicals have a very low tendency for rearrangement, mostly non-rearranged products are formed during reactions done at high temperatures.[6] It was surprising to us that, even at 150 °C, only rearranged products **11** and **12** were formed in a ratio of 2:1.

To rationalize the formation of the isomeric bromides **11**/**12**, we propose the following mechanism. Electrophilic bromine can attack the double bond in **4** from both the *endo* and *exo* face of the double bond. It is evident from the configuration of the bromine atoms in **11**/**12** that the initial attack by bromine has occurred from the *endo* face (*endo* is referred to as the side of the benzene ring) of the double bond to form **17** (Scheme 4). The formed bromonium ion **17** can rearrange to the non-classical carbocation **18**, which can be trapped by the bromide anion to give the product **12**. In the case of the formation of an *exo*-bromonium ion, the system would undergo an aryl shift. Such an *exo*-bromonium ion has not been formed, as we have never found any products which would be formed from the aryl shift.

Computational Methods: In order to understand the unusual behavior of this hydrocarbon **4**, we performed a series of density functional theory calculations with Becke's three-hybrid method (B3)[11] and the Lee−Yang−Parr exchange functional (B3LYP),[12] as implemented in the GAUSSIAN 03W package program.[13] The geometry optimizations of studied molecules were achieved at the B3LYP/6-31G(d) level, which is very successful in modeling polycyclic systems[14] and in predicting the degree of

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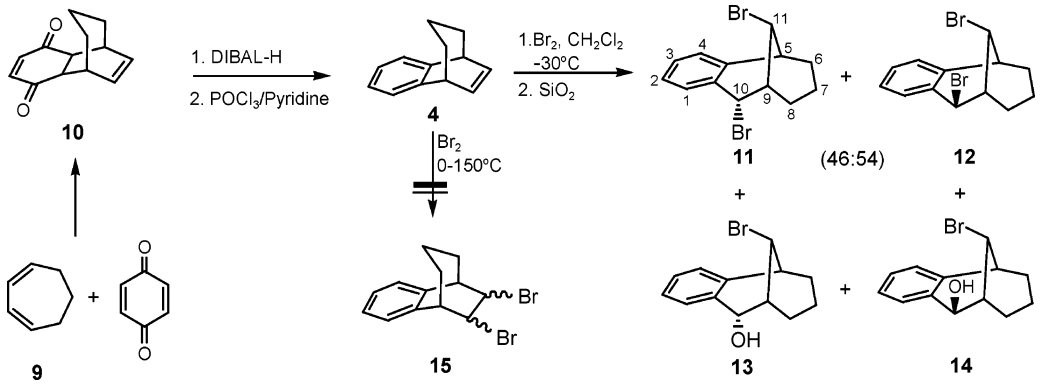
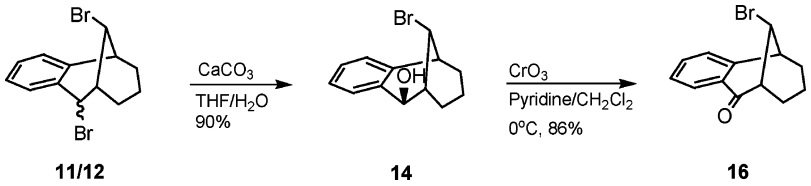
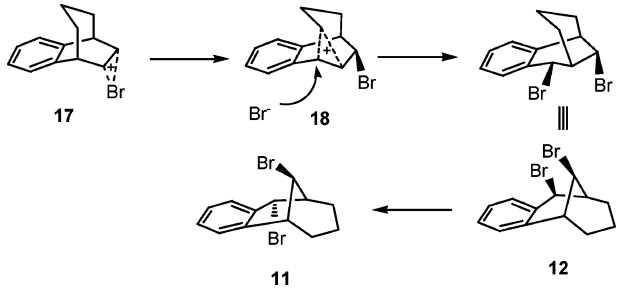
SCHEME 2



SCHEME 3



SCHEME 4



pyramidalization of the double bond.[15] Stationary points were characterized as minima or transition structures by way of an analytic evaluation of harmonic vibrational frequencies at the level of geometry optimization. All energies reported in the results and discussions were calculated at the B3LYP/6-31G-(d) level and include unscaled zero-point vibrational energies.

The double bonds in norbornadiene **19** and benzonorbornadiene **6** are pyramidalized[16] in the *endo* direction (*endo* refers to the motion of the vinyl hydrogens to the side of the benzene ring) about 3.35 and 5.20°, respectively (Table 1). As the pyramidalization angle, we will use the butterfly angle ψ, which is defined as $\psi = 180° - |D_1|$. The dihedral angle (D_1) is defined by the bonding sequence 1−2−3−4 (Figure 1). Norbornadiene (**19**) and benzonorbornadiene (**6**) exclusively undergo an *exo* attack upon treatment with bromine. This observed *exo* selectivity[17] in norbornene, norbornadiene, and benzonorbornadiene and related compounds is certainly not surprising since both electronic and steric factors would be expected to favor attack on the convex face of the pyramidalized double bond.[18] By going from benzonorbornadiene **6** to benzobarrelene **22**, the bending angle is changed from 5.2 to 1.36° and the direction of the pyramidalization remains constant. The bromination of benzobarrelene **22** at 0 °C gave products derived from the *exo* attack as well as the *endo* attack in a ratio of 3:1.[4i] The

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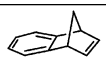
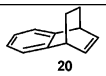
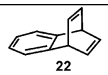
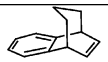
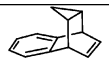
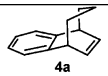
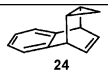
TABLE 1. Energies Including Zero-Point Vibrational Corrections (in hartree/particle) and Pyramidalization Angles of Optimized Molecules at the B3LYP/6-31G(d) Level

Compounds	 19	 6	 20	 22	 4	 23	 4a	 24
Energy	-271.348315	-424.967872	-464.277472	-463.058191	-503.563245	-502.334607	-503.562714	-502.336161
Dihedral angle ($C_1C_2C_3H_4$)	-176.65	-174.80	178.34	-178.64	177.60	179.95	178.38	178.63
Butterfly bending angles	3.35	5.20	-1.66	1.36	-2.4	-0.05	-1.62	-1.37
Direction of Pyramidalization	*endo*	*endo*	***exo***	*endo*	***exo***	***exo***	***exo***	***exo***

exo attack is the dominating route because of the *endo* pyramidalization of the double bond. The product distribution is in agreement with the direction of the pyramidalization of

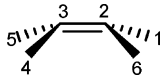
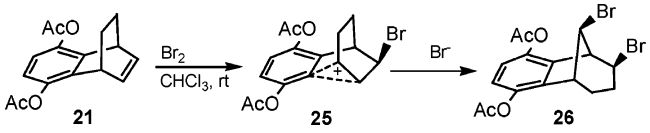


FIGURE 1. Definition of the dihedral angle.

the double bond in **22**. Recently, Smith[19] has reported the bromination of diacetoxy dihydrobenzobarrelene **21** and found that a single stereospecifically dibromide **26** was formed. The double bond in the parent hydrocarbon **20** is about 1.66° *exo* pyramidalized. The formation of **26** can be rationalized by the *exo* attack of bromine despite the *exo* pyramidalization of the double bond (Scheme 5).

SCHEME 5



Smith has suggested an asynchronous concerted process involving an ion pair as the transition structure. Furthermore, it has been shown that the energy gap between the transition state derived from the *exo* attack and that of *endo* attack is about 28.1 kcal/mol since the former one results directly in the formation of phenonium ion **25**. These findings indicate that the direction of the pyramidalization alone does not determine the direction of the attack of bromine on the double bond. Other factors also play important roles. Next, we have calculated the pyramidalization of the double bond for the conformers **4** and **4a**.

The calculated isomerization energy barrier and energy difference for these conformers are about 5.38 and 0.33 kcal/mol, respectively, whereas the *endo* isomer **4** is favored (Figure 2).

The pyramidalization angle in the *endo* isomer **4** is 2.4°, and in the case of the *exo* isomer **4a**, it is 1.62°, and the double bonds in both cases are *exo* pyramidalized. For comparison,

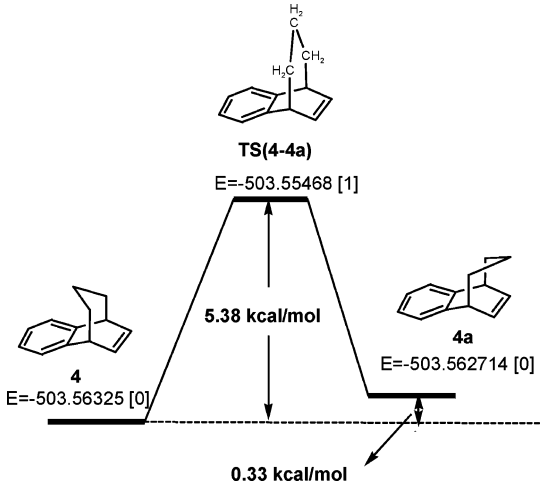
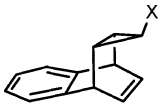


FIGURE 2. The calculated inversion barrier of **4** to **4a** (energies including zero-point corrections, in hartree/particle, and the number of imaginary frequencies are in brackets).

we have replaced the propylene units in **4** and **4a** with a cyclopropane ring to form **23** and **24** and have shown that annelation of a cyclopropane ring decreases the pyramidalization angles to 0.05 and 1.37°, respectively, and the direction of the pyramidalization is not changed.

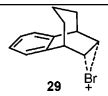
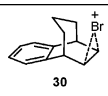
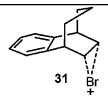
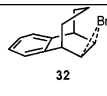
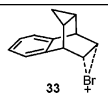
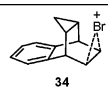
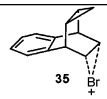
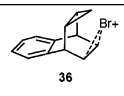
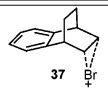
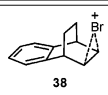
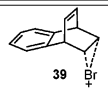
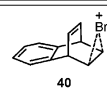
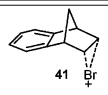
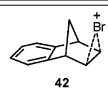
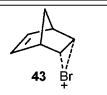
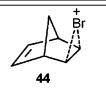


27 X = CN
28 X = $COOCH_3$

Recently, we reported the bromination reactions of **27** and **28** and noticed that the products are formed only from *endo* attack.[20] The double bonds in **20** and **24** have almost similar pyramidalization angles (1.66 and 1.37°), and they are bent in the *exo* direction. The *endo* attack on the double bonds in **27**

(20) Menzek, A.; Saracoglu, N.; Dastan, A.; Balci, M.; Abbasoglu, R. *Tetrahedron* **1997**, *53*, 14451.

TABLE 2. Energies of the Bromine−Cation Complexes (in hartree/particle) Including Zero-Point Corrections and Energy Differences (in kcal/mol) for Molecule Isomers (29−32, 33−36) and Molecule Pairs (37−38, 39−40, 41−42, 43−44) at the B3LYP/6-31G(d) Level

Bromine-Cation Complexes								
	29	**30**	**31**	**32**	**33**	**34**	**35**	**36**
Energy Values	-3075.00553	-3075.00118	-3075.00223	-3074.99260	-3073.77566	-3073.77958	-3073.76865	- 3073,76801
Energy Differences	0.00	2.73	2.07	8.11	2.46	0.00	6.86	7.26
Bromine-Cation Complexes								
	37	**38**	**39**	**40**	**41**	**42**	**43**	**44**
Energy Values	-3035.71370	-3035.71825	-3034.49892	-3034.50110	-2996.39786	-2996.41420	-2842.77825	-2842.79120
Energy Differences	2.85	0.00	1.37	0.00	10.25	0.00	8.13	0.00

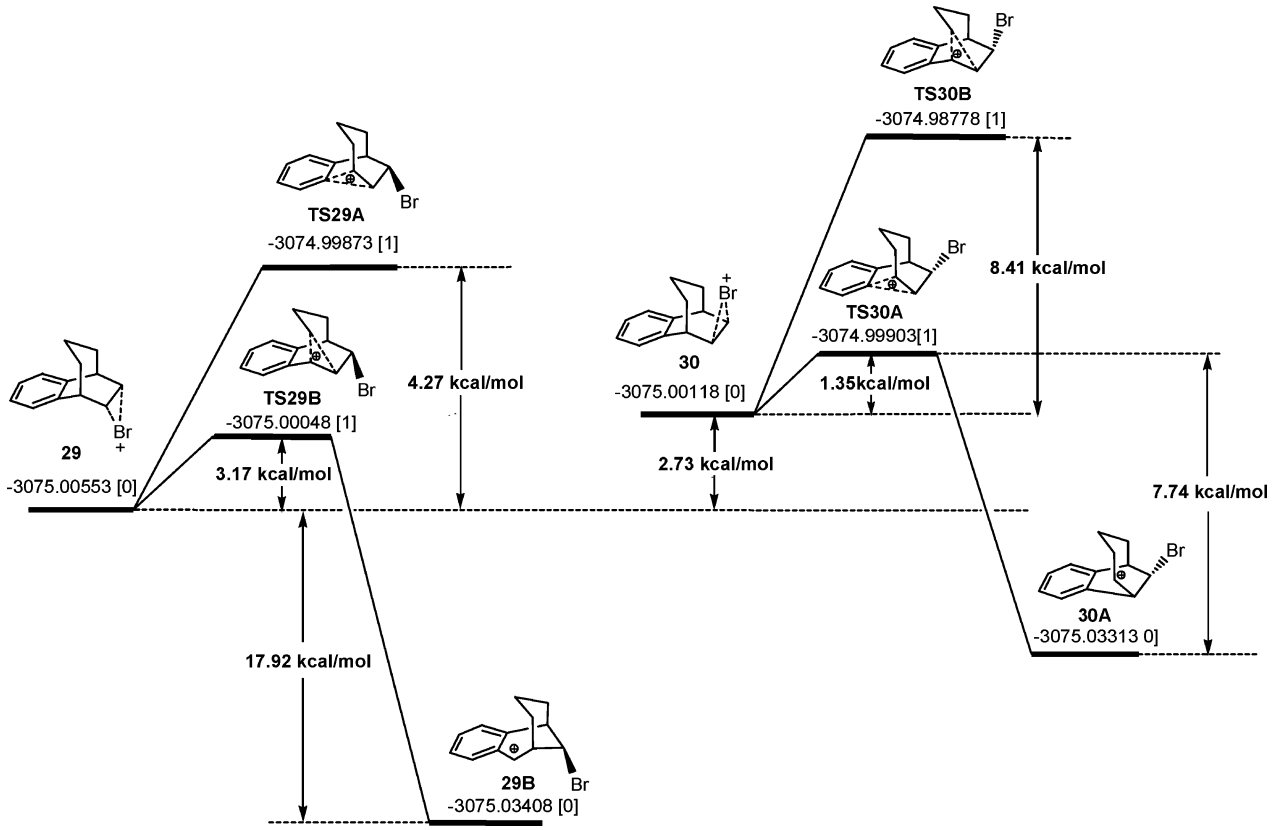
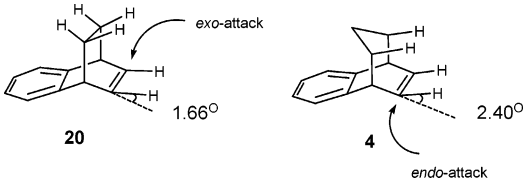


FIGURE 3. The possible reaction paths for the bromonium ions **29** and **31** (energies including zero-point corrections, in hartree/particle, and number of imaginary frequencies are in brackets).

and **28** cannot be only attributed to the *exo* pyramidalization. The cyclopropane rings in **27**/**28** prevent the *exo* attack of bromine to the double bond. However, the diacetoxy derivative **21** (a derivative of **20**) exclusively undergoes *exo* attack.

Both of the double bonds in the conformers **4** and **4a** are pyramidalized in the *exo* direction. The propylene unit in **4a** would prevent the *exo* attack as in the case of **27** and **28**. The conformer **4** shows a higher degree of the pyramidalization (2.4°) of the double bond in the *exo* direction. Therefore, it is expected that bromine would attack the double bond in **4** from the *endo* face of the double bond. As discussed above, **4** exclusively undergoes *endo* attack. Furthermore, we assume that the methylenic hydrogens in **4** also hinder the approach of the bromine from the *exo* face of the double bond.



However, if we compare the bending angle of the double bond in **4** (2.4°) with the bending angle in **20**, the exclusively

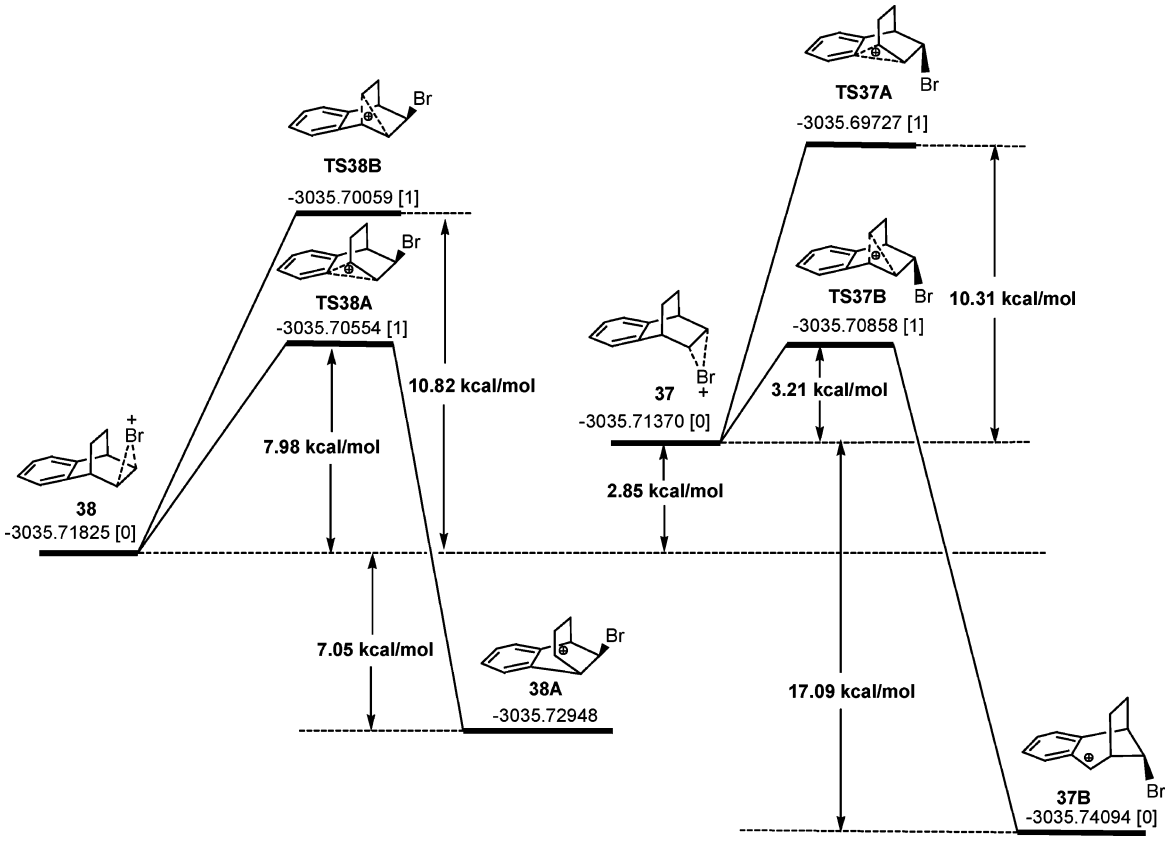


FIGURE 4. The possible reaction paths for the bromonium ions **37** and **38** (energies including zero-point corrections, in hartree/particle, and number of imaginary frequencies are in brackets).

exo attack on the double bond in **20** cannot be interpreted based on the double bond pyramidalization. The absence of products derived from the *endo* attack on the double bond in **20** indicates that the formation of a phenonium ion such as **25** is the major driving force for the formation of **26**. We assume that the steric hindrance caused by the propylene units in **4** as well as in **4a** hinders the formation of a phenonium ion such as **25**, in other words the *exo* attack.

Furthermore, we have calculated the reaction paths for the bromination of **4** and **20**. First, we determined the relative energies of the bromonium ions derived from the *endo* as well as the *exo* attacks of bromine on the different conformers of **4** and **4a**; this was also carried out on compound **20**. It was found that the bromonium ions **29** derived from the *endo* attack of bromine on the conformer **4** and **38** derived from the *exo* attack on **20** are the most stable ones, which is in agreement with the products formed in the bromination reaction of **4** and **20** (Table 2). The calculations of the relative energies of the other bromine−cation complexes for molecule isomers, **37**−**38**, **39**−**40**, **41**−**42**, and **43**−**44**, at the B3LYP/6-31G(d) level also indicated that the bromination reactions proceed from the most stable bromonium ions (Table 2). After this, the transition structures for formations of their phenonium ions and non-classical carbocations starting from the *endo*- and *exo*-bromonium ions **29** and **30** (Figure 3) and **37** and **38** (Figure 4) were calculated.

For the bromonium ion **29**, we found that the related transition structures, **TS29A** and **TS29B**, have imaginary frequency 1. For the formation of **29B**, an activation energy of 3.17 kcal/mol (with respect to the energy of **29**) is required. On the other hand, 4.27 kcal/mol is required for the formation of **TS29A** with respect to the energy of **29**. However, for the formation of the phenonium ion, **TS30A** requires an activation energy of only 1.35 kcal/mol. This process would generate a classical carbocation **30A**, which would be trapped by a bromide anion. Such a product was not detected in the reaction products. Therefore, we assume that the bromine attacks the double bond in **4** exclusively from the *endo* face of the molecule.

We ran similar calculations for bromonium ions **37** and **38** and determined the related transition structures, **TS38A** and **TS37B**, having imaginary frequency 1. The formation of phenonium ion **TS38A** needs less energy (7.98 kcal/mol) than the formation of **TS38B**, which requires 10.82 kcal/mol so its formation is more plausible. The *endo*-bromonium ion **37** can undergo only an alkyl shift to form a non-classical carbocation. The activation barrier for the corresponding transition state **TS37B** is 3.21 kcal/mol. One would expect that the reaction would follow this reaction path and generate benzylic cation **37B**. Such a product was also not found in the reaction products.

In summary, the *exo* pyramidalization of the double bond in **4** and the steric hindrance caused by the propylene group together are responsible for the exclusively *endo* selectivity of the double bond in **4**, as opposed to benzonorbornadiene **6** and dihydrobenzobarrelene **20**, where exclusively *exo* selectivity is observed. The configurations that initially formed bromonium ions determine the outcome of the reactions.

Experimental Section

Caution: It has been reported[21] that of the three laboratory workers who have used dibromides and a bromohydrin derived from norbornadiene two later developed pulmonary disorders, which

contributed to their subsequent deaths. The third person exhibited a minor skin sensitivity reaction. In the case of dibromide derived from benzonorbornadiene, there is no report in the literature about the toxicological effects. However, we recommend that the compounds must be handled with extreme caution.

Bromination of 6,7,8,9-Tetrahydro-5*H*-5,9-ethenobenzo[*a*][7]annulene (4): To a magnetically stirred solution of **4**[9] (1.5 g, 8.81 mmol) in 40 mL of dry CH_2Cl_2 at −30 °C was added dropwise a cold solution of bromine (1.41 g, 8.81 mmol) in 2 mL of CH_2Cl_2. The reaction mixture was stirred for an additional 25 min at −30 °C. The solvent was evaporated. The ^{1}H NMR spectrum of the residue showed the formation of **11** and **12** in a ratio of 46:54, respectively. The residue was chromatographed on silica gel (40 g) eluting with *n*-hexane.

The first fraction: **(5*S*(*R*),9*S*(*R*),10*R*(*S*),11*R*(*S*))-10,11-dibromo-5,6,7,8,9,10-hexahydro-5,9-methanobenzo[*a*][8]annulene (11):** Yield 1.4 g, 48%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.72 (br d, J = 7.7 Hz, 1H,), 7.31−7.23 (m, 2H), 6.98 (br d, J = 7.2 Hz, 1H), 6.06 (d, $J_{9,10}$ = 6.2 Hz, 1H), 4.75 (t, $J_{5,11}$ = $J_{9,11}$ = 3.1 Hz, 1H), 3.37 (m, 1H), 2.67 (m, 2H), 2.00 (m, 1H, 1H), 1.82 (m, 2H), 1.43−1.20 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 137.5, 136.7, 130.2, 128.5, 128.5, 127.3, 57.5, 54.8, 44.5, 42.4, 35.4, 32.9, 15.8; IR (NaBr, liquid) 3020, 2934, 1488, 1445, 1453, 1286, 1271, 1260, 1176, 1075, 959. Anal. Calcd for $C_{13}H_{14}Br_2$: C, 47.31; H, 4.28. Found: C, 47.07; H, 4.23.

The ^{1}H NMR spectral data for **12** were extracted from a mixture of **11** and **12**. **(5*S*(*R*),9*S*(*R*),10*S*(*R*),11*R*(*S*))-10,11-dibromo-5,6,7,8,9,10-hexahydro-5,9-methanobenzo-[*a*][8]annulene (12):** ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.66 (br d, J = 7.7 Hz, 1H), 7.31−7.23 (m, 2H), 7.06 (br d, J = 7.3 Hz), 5.42 (s, 1H), 4.65 (t, $J_{5,9}$ = $J_{9,11}$ = 2.8 Hz, 1H), 3.50 (m, 1H), 3.17 (m, 1H), 1.90−0.90 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 137.5, 136.7, 130.2, 128.5, 128.5, 127.3, 57.5, 54.8, 44.7, 42.5, 35.4, 32.9, 15.7.

The next fraction was identified as **(5*S*(*R*),9*R*(*S*),10*R*(*S*),11*R*(*S*))-11-bromo-5,6,7,8,9,10-hexahydro-5,9-methanobenzo[*a*][8]annulen-10-ol (14):** Yield 494 mg, 21%; mp 65−66 °C, colorless crystals from chloroform/*n*-hexane (1:1); ^{1}H NMR (400 MHz, CD_3OD) δ 7.53 (br d, J = 7.4 Hz, 1H), 7.30−7.22 (m, 2H), 7.08 (br d, J = 7.0 Hz), 4.72 (t, $J_{5,11}$ = $J_{9,11}$ = 3.0 Hz), 4.57 (s, 1H), 3.38 (m, 1H), 2.69 (m, 1H), 1.96−1.65 (m, 4H), 1.29 (m, 1H), 0.91 (m, 1H); ^{13}C NMR (100 MHz, CD_3OD) δ 138.7, 136.8, 128.7, 128.4, 127.8, 126.7, 70.7, 52.7, 45.0, 45.0, 34.2, 33.4, 16.0; IR (NaBr, liquid) 3557, 3448, 2931, 2861, 1487, 1455, 1397, 1256, 1229, 1024, 958. Anal. Calcd for $C_{13}H_{15}BrO$: C, 58.44; H, 5.66. Found: C, 58.32; H, 5.45.

The last fraction was **(5*S*(*R*),9*R*(*S*),10*S*(*R*),11*R*(*S*))-11-bromo-5,6,7,8,9,10-hexahydro-5,9-methanobenzo[*a*][8]annulen-10-ol (13):** Yield 71 mg, 3%; ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.62 (br d, J = 7.6 Hz, 1H), 7.31−7.24 (m, 2H), 7.05 (br d, J = 7.0 Hz, 1H), 5.36 (d, $J_{9,10}$ = 6.6 Hz, 1H), 4.74 (t, $J_{5,11}$ = $J_{9,11}$= 3.3 Hz, 1H), 3.38 (m, 1H), 2.60 (m, 1H), 2.27 (br d, J = 11.9 Hz, 1H), 1.97−0.90 (m, 5H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 141.3, 138.8, 130.1, 129.8, 129.0, 127.8, 71.2, 59.6, 46.3, 43.2, 37.7, 30.0, 18.3; IR (NaBr, liquid) 3375, 2933, 2853, 1490, 1453, 1443, 1287, 1261, 1044, 1027, 960. Anal. Calcd for $C_{13}H_{15}BrO$: C, 58.44; H, 5.66. Found: C, 58.25; H, 5.33.

Bromination of 4 at 150 °C: 300 mg (1.76 mmol) of **4** was dissolved in 4 mL of decalin in a 25 mL two-necked flask. The flask was equipped with a reflux condenser and an inlet glass tube touching the bottom of the reaction flask. The inlet glass tube was connected to a 2 mL round-bottom flask that contained 282 mg (1.76 mmol) of bromine. Bromine vapors, obtained by heating of the flask to 100 °C, were transferred directly to a decalin solution, which was heated to 150 °C, for 20 min while stirring magnetically. The color due to the bromine disappeared immediately. The solvent was removed under reduced pressure. ^{1}H NMR analysis indicated the formation of **11** and **12** in a ratio of 2:1, respectively.

Hydrolyses of Dibromides 11/12: A suspension of dibromides **11/12** (374 mg, 1.13 mmol) and $CaCO_3$ (410 mg, 4.10 mmol) in THF (5 mL) and H_2O (5 mL) was refluxed for 30 h. After the reaction mixture was cooled to room temperature, the insoluble materials were separated by filtration. The filtrate was extracted with chloroform (2 × 50 mL), washed with water, and dried over $MgSO_4$. The residue was removed, and the hydroxy bromide **14** was formed as the sole product (272 mg, 90%).

Oxidation of 14: A solution of CrO_3 (341 mg, 3.41 mmol) in pyridine/CH_2Cl_2 (2 mL, 1:1) was cooled to 0 °C. Then hydroxy bromide **14** (140 mg, 0.53 mmol) in CH_2Cl_2 (4 mL) was added dropwise. The mixture was stirred at 0 °C for 2 h and then rt for 24 h, and then the solvent was evaporated. The residue was filtered over silica gel (5 g) eluting with *n*-hexane/EtOAc (95:5) to give pure ketone **16** (120 mg, 86%). **(5*S*(*R*),9*R*(*S*),11*S*(*R*))-11-Bromo-6,7,8,9-tetrahydro-5,9-methanobenzo[*a*][8]annulen-10(5*H*)-one (16):** mp 93−94 °C, pale yellow crystals from chloroform/*n*-hexane (1:2); ^{1}H NMR (200 MHz, $CDCl_3$) δ 8.00 (br d, J = 7.6 Hz, 1H), 7.50 (m, 1H), 7.32 (m, 1H), 7.18 (br d, J = 7.7 Hz, 1H), 4.68 (t, $J_{5,11}$ = $J_{9,11}$ = 3.0 Hz, 1H), 3.51 (m, 1H), 3.09 (m, 1H), 2.03−1.73 (m, 4H), 1.38 (m, 1H), 1.11 (m, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 199.8, 144.9, 136.4, 135.2, 130.8, 129.3, 127.8, 58.0, 54.0, 46.2, 34.6, 33.5, 18.1; IR (KBr, cm^{-1}) 2937, 2858, 1687, 1599, 1457, 1293, 1250, 988. Anal. Calcd for $C_{13}H_{13}BrO$: C, 58.89; H, 4.94. Found: C, 58.60; H, 4.76.

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Supporting Information Available: ^{1}H and ^{13}C NMR spectra for all new compounds, Cartesian coordinates, and energy values for the optimized structures: **4**, **4a**, **5**, **19**, **20**, **22**−**24**, **29**−**32**, **TS29A**, **TS29B**, **TS31A**, **TS31B**, **TS37A**, **TS37B**, **TS38A**, **TS38B**, **29B**, **31A**, **37B**, and **38A** at the B3LYP/6-31G(d) level. This material is available free of charge via the Internet at http://pubs.acs.org.

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