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Stereochemical Memory in the Temperature-Dependent Photodenitrogenation of Bridgehead-Substituted DBH-Type Azoalkanes: Inhibition of Inverted-Housane Formation in the Diazenyl Diradical through the Mass Effect (Inertia) and Steric Hindrance

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Abstract: The photochemical denitrogenation of the cyclopentene-annelated DBH-type azoalkanes **1** has been examined in solution as a function of bridgehead substitution and temperature. For all derivatives, namely, the unsubstituted **1a**(H/H), monomethyl **1b**(Me/H) dimethyl **1c**(Me/Me), monophenyl **1d**(Ph/H), and diphenyl **1e**(Ph/Ph), the temperature-dependent ratio of syn and anti housanes **2** provides experimental support for a competition between the singlet (high temperature) and triplet (low temperature) reaction channels in the direct photolysis. The syn/anti ratio of the housanes **2** depends on the extent and type of bridgehead substitution; the amount of the anti diastereomer (retention) follows the order Ph > Me > H, and double substitution is more effective than single. This stereochemical memory is interpreted in terms of the mass effect (inertia) of the substituents and steric interaction (size) between the substituents at the bridgehead and the methylene bridge during the deazetation step of the transient diazenyl diradical conformations ^{1}**DZ** (*exo-ax*) and ^{1}**DZ** (*exo-eq*). These conformers are impulsively generated upon decay of the ^{1}(n,π*)-excited azoalkane, a trajectory assessed through computational work. The new mechanistic feature disclosed by the unprecedented anti stereoselectivity (retention) is the intervention of a puckered 1,3-cyclopentanediyl singlet diradical ^{1}**DR** as product bifurcation step, whose conformational relaxation to the planar species (loss of stereochemical memory) is encumbered by bridgehead substitution.

Introduction

The nitrogen extrusion of azoalkanes is a complex and intriguing process that has attracted much attention for the last almost forty years.[1−7] Initially, Roth and Martin[1a] reported that in the gas-phase thermolysis of *exo*-deuterated diazabicyclo-[2.2.1]heptene (d_2-**DBH**), the inverted *exo*-deuterated bicyclo-[2.1.0]pentane (exo housane) is formed as the major product (Scheme 1). It was also shown that in the liquid-phase photolysis inversion dominates.

Several mechanisms have been postulated to explain this unusual stereochemical preference (Scheme 1): The S_H2 process[1b] involves the stepwise cleavage of the two C−N bonds, with the singlet diazenyl diradical (^{1}**DZ**) as the key intermediate.[6] Concerted backside displacement (analogous to the S_N2 mechanism[1c]) of the nitrogen molecule by the carbon-radical site affords the inverted exo housane. In competition, denitro-

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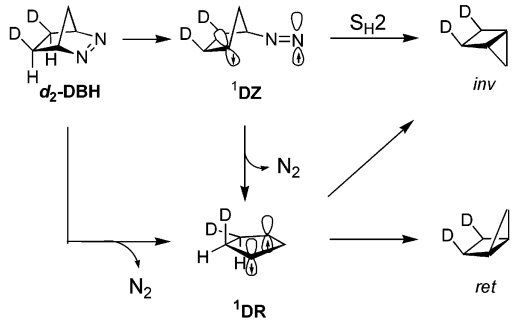
Scheme 1



genation leads to the C_2-symmetric[2d] singlet 1,3-cyclopentanediyl diradical **^{1}DR**, which collapses to both the retained and inverted housanes in equal amounts. Alternatively, in recent work the dynamic model for the thermolysis of **DBH** has been proposed, in which the intervention of the singlet diazenyl diradical **^{1}DZ** was questioned on the basis of computational results.[8] It was concluded that the thermal denitrogenation of **DBH** proceeds directly to a nonstatistical **^{1}DR** intermediate by concerted cleavage of both CN bonds (Scheme 1), for which prevalent inversion was rationalized in terms of the previously proposed momentum conservation.[1d]

Qualitative considerations in terms of Dauben−Salem−Turro theory[9] suggest that the photochemical azoalkane denitrogenation[6a,d] proceeds stepwise. Indeed, our new computational results indicate that the inverted housane may be formed from the **^{1}DZ** intermediate by the S_H2 process (Scheme 1). While a detailed account of these computations will be given elsewhere, here we report the computed reaction coordinate that describes the singlet-excited-state evolution and the ground-state relaxation of the ^{1}(n,π*)-excited **DBH** (Scheme 2).[10] In this scheme are given the computed structures of the *exo-axial* [σ,σ-**^{1}DZ** (*exo-axial*)] and *exo-equatorial* [σ,σ-**^{1}DZ** (*exo-equatorial*)] conformations and their relative energies (kcal/mol) along the reaction coordinate (^{1}n,π*, σ,π-**DZ**-like and $\sigma,\pi/\sigma,\sigma$ have been taken from ref 5a). Our computations predict that the initially generated *exo-axial* σ,σ-**^{1}DZ** intermediate transforms to the slightly higher-energy (0.7 kcal/mol) exo-equatorial conformation with an activation barrier of ca. 4.5 kcal/mol, the species destined to afford inverted housane along the S_H2 process.

In the computed structures, the C-7 methylene group in **DBH** (the molecular fragment that undergoes the largest displacement) is shown in front views, side views have been chosen for the cyclopentyl envelopes, in which the substituents have been omitted to help visualize the conformational changes during the inversion process. The ^{1}(n,π*)-excited azoalkane breaks first one of the CN bonds[5a,5b] to reach a transition state with singlet σ,π-**DZ** diradical character in the endo configuration of the diazenyl functionality.[5a] This appears to be a general feature in the α cleavage of ^{1}(n,π*)-excited azoalkanes, as demonstrated for pyrazoline and 2,3-diazabicyclo[2.2.2]octane.[5b] After the transition state has been reached, the molecule evolves toward a conical intersection (CI), located ca. 25 kcal/mol lower in energy, where the σ,π and σ,σ states of the **^{1}DZ** diradical cross. Decay to the ground state through the conical intersection leads to the region of a singlet σ,σ-**DZ** structure in the exo-axial configuration, which is located ca. 40 kcal/mol below the same transition state. Since the reaction coordinate is substantially dominated by a change in the C−N−N angle (i.e., the endo-to-exo motion), a considerable fraction of the 50 kcal/mol of kinetic energy is initially deposited in the C−N−N bending mode of the σ,σ-**DZ** species. We argue that the apparent coupling between C−N−N bending and the axial-to-equatorial torsion will impulsively displace the exo-axial conformation toward the exo-equatorial to generate ultimately the inverted housane. In contrast to the thermally activated process,[8] a reaction coordinate that describes the simultaneous breaking of both CN bonds in the azoalkane has not been located in the photochemical process.

The mechanistic implications of these computations[10] on the photodenitrogenation of DBH are displayed in Scheme 3. Passage through the conical intersection generates first the **^{1}DZ** (*exo-ax*) diradical as bona fide intermediate, which generates the **^{1}DZ** (*exo-eq*) species. The latter leads to the inverted housane by means of backside attack along the S_H2 coordinate (a 2.2 kcal/mol barrier has been computed[10] for this process). Alternatively, the **^{1}DZ** (*exo-ax*) intermediate loses N_2 to afford initially the puckered singlet 1,3-cyclopentanediyl diradical **^{1}DR**(puckered), which is predestined to cyclize into the retained housane (stereochemical memory effect). In competition, the **^{1}DR**(puckered) transient relaxes to the C_2-symmetric **^{1}DR**(C_2) diradical, from which the retained and inverted housanes are produced in equal amounts. Recent experimental work on the viscosity dependence of the stereoselectivity in the photodenitrogenation of **DBH** derivatives confirmed the intermediacy of the singlet diazenyl diradical **^{1}DZ**.[11]

In a related study on the photodenitrogenation of the more complex cyclopentene-annelated DBH-type azoalkane **1a**,[7] also a diazenyl diradical **^{1}DZ** was invoked to rationalize the unusual temperature dependence on the product ratio of inverted (syn) versus retained (anti) housanes **2a** (Scheme 4). While at low temperature, isc from ^{1}**1**(n,π*) to the triplet-excited state ^{3}**1**(n,π*) is the major process (path B), at high temperature the isc is circumvented, presumably because of efficient α-CN bond cleavage to the diazenyl diradical **^{1}DZ**. The latter undergoes ring closure along the S_H2 pathway to afford the inverted *syn*-**2** housane. To understand the mechanistic intricacies of this stereoselective inversion process, we have now examined the bridgehead substituent effect on the syn/anti-housane ratio in the photodenitrogenation of the unsymmetrical monomethyl- and monophenyl-substituted azoalkanes **1b**(Me/H) and **1d**(Ph/H), as well as the symmetrical dimethyl and diphenyl derivatives

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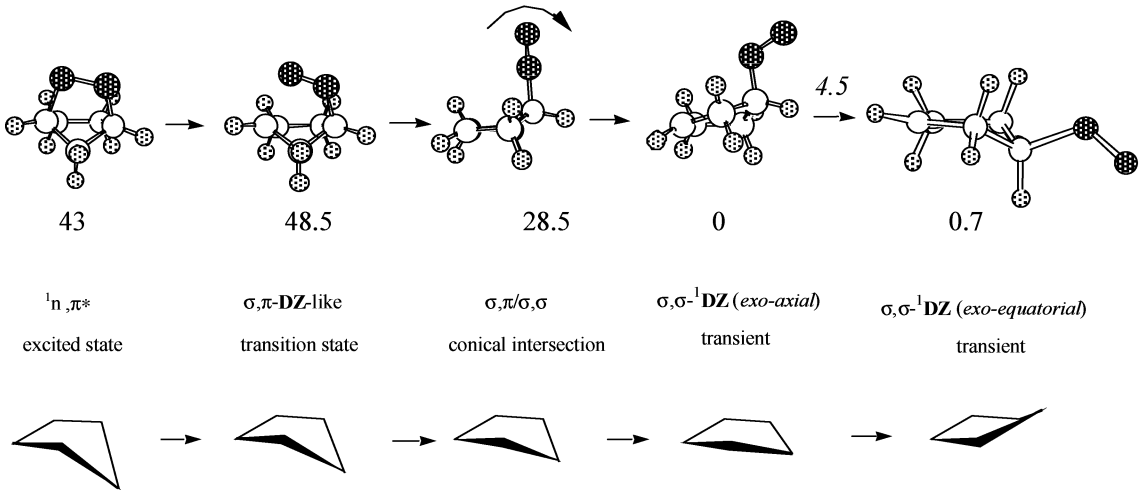
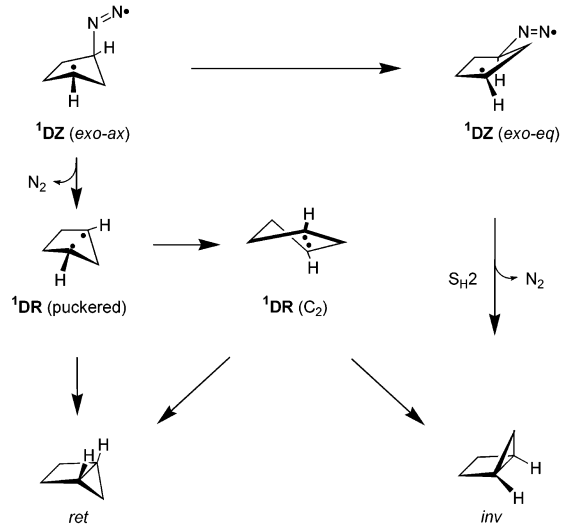
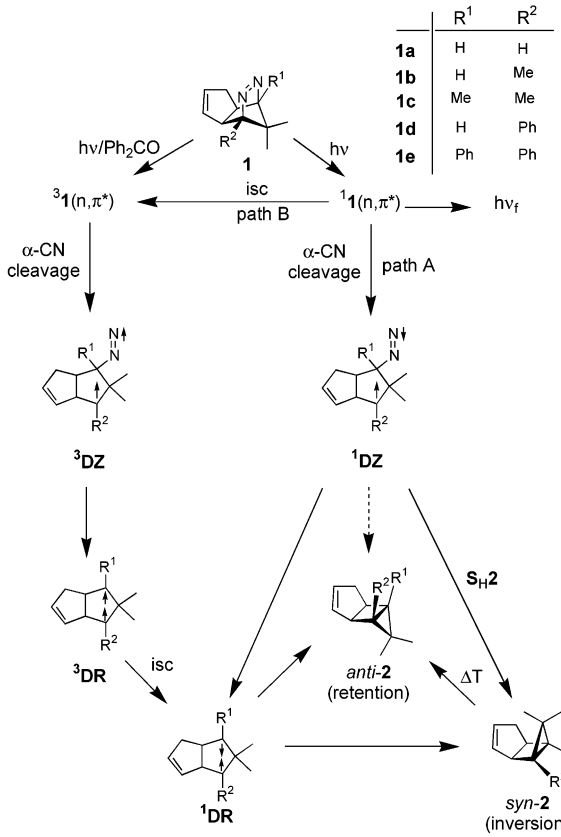
Scheme 2



Scheme 3



Scheme 4



1c(Me/Me) and **1e**(Ph/Ph). We demonstrate that the temperature dependence of the syn/anti product ratio is a general feature in the photolysis of these azoalkanes, irrespective of the extent and type of bridgehead substitution. Equally mechanistically significant, the present set of azoalkane derivatives requires an additional product-branching point (dashed arrows in Scheme 4) for the transient ^{1}**DZ** structure, which modifies the product distribution by enhancing the amount of anti housane **2** in the order of the mass and the steric demand of the bridgehead substituent: **1e**(Ph/Ph) > **1d**(Ph/H) > **1c**(Me/ Me) > **1b**(Me/ H) > **1a**(H/H). We propose that the mass of the bridgehead substituents and their steric interactions with the gem-dimethyl group in the ^{1}**DZ** diradical effectively encumber the ring-inversion motion prompted by the excited-state relaxation (Scheme 2) and are, therefore, responsible for these unprecedented product data. Exclusive retention, as observed for the diphenyl derivative **1e**, has hitherto not been documented in solution. In fact, only in the confined space of the crystal lattice was mainly, but not exclusively, retention found in the photodenitrogenation of d_2-**DBH**.[1a]

Results

The azoalkanes **1** were prepared according to the Hünig route,[12] of which all but the monophenyl derivative **1d** are known; the latter was fully characterized (cf. Supporting Information). The housanes *anti*- and *syn*-**2a** were obtained as reported,[7,13] the remaining anti- and syn-housanes **2** were fully characterized by spectroscopic methods (cf. Supporting Information). The configuration of the anti housanes was assigned by means of an NOE effect between the syn-methyl group and the C1-bridgehead hydrogen atom, and for the syn diastereomer, between the anti-methyl group and the C6,7-methylene *exo*-hydrogen atoms. Additional support for this assignment comes

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from the quantitative thermal isomerization of the syn diastereomers to the persistent anti housanes.[7,14]

The activation parameters for the syn-to-anti isomerization of the housanes **2** were determined in toluene to be $E_a = 29 \pm 2$ kcal/mol and $\log A = 12.6 \pm 0.9$ s^{-1} for the housane **2a**, $E_a = 26 \pm 2$ kcal/mol and $\log A = 12.5 \pm 0.9$ s^{-1} for **2b**, $E_a = 23 \pm 2$ kcal/mol and $\log A = 12.4 \pm 0.9$ s^{-1} for **2c,** and $E_a = 22 \pm 2$ kcal/mol and $\log A = 12.9 \pm 0.9$ s^{-1} for **2d** (cf. Supporting Information). For the thermally labile diphenyl derivative **2e** (half-life of ca. 100 min at −30 °C and ca. 190 s at 0 °C), only approximate activation parameters could be estimated, namely, E_a ca. 18 kcal/mol and $\log A$ ca. 12 s^{-1}. Clearly, the thermal persistence of the syn housanes decreases regularly with bridgehead substitution; the order is **2a** > **2b** > **2c** ≅ **2d** > **2e**.

The activation parameters for the α-CN-bond cleavage of the ^{1}(n,π*)-excited azoalkanes **1a**, **c** were determined from temperature-dependent fluorescence quantum yields (ϕ_f),[15] measured in methylcyclopentane against anthracene as standard (cf. Supporting Information). A plot of $\ln \phi_f^{-1}$ against the inverse absolute temperature is linear ($R^2 = 0.980$). From these data and the relation in eq 1 (k_f is the fluorescence rate constant),

$$\ln (1/\phi_f) = -E_a/RT + \ln (A/k_f) \qquad (1)$$

the activation energy of the α-CN bond cleavage was determined to be $E_a = 2.08 \pm 0.04$ kcal/mol and $\log A = 13.2 \pm 0.2$ s^{-1} for **1a**;[16] for **1c** they are $E_a = 1.18 \pm 0.04$ kcal/mol and $\log A = 11.0 \pm 0.2$ s^{-1}. The activation parameters were not measured for the unsymmetrical azoalkane **1b**. Unfortunately, the fluorescence quantum yields of the phenyl-substituted derivatives **1d** and **1e** are too low, nor are their syn housanes sufficiently thermally persistent, to determine the activation parameters of the CN-bond cleavage.[7]

The results of the product studies for the azoalkanes **1** as a function of temperature and reaction mode (direct, benzophenone-sensitized, and *trans*-piperylene-quenched photolyses) are presented in Table 1. As reported previously for the **1a** derivative,[7] mixtures of the anti and syn housanes were also obtained for the other azoalkanes **1b**−**e**. Unquestionably, the syn/anti ratio depends on the temperature and the reaction mode. At high temperatures, the direct photolysis of the azoalkane **1a** affords preferably the syn isomer (entry 1),[7] while for **1b**−**e** the anti dominates (entries 7, 13, 19, and 24). Clearly, the amount of anti housane follows the order **2e** > **2d** > **2c** > **2b** > **2a**. In contrast, at low temperature (−75 °C), the direct photolysis leads to similar syn/anti ratios for the azoalkanes **1a**−**d** (entries 3, 9, 15, and 20), with a slight preference of the anti housane. For the diphenyl derivative **1e**, even more syn isomer has been obtained (entry 25). These syn/anti ratios are within the experimental error about the same as those for the benzophenone-sensitized photolysis (entries 4, 10, 16, 21, and 26). Moreover, the *trans*-piperylene-quenched photolyses show that the conversion of the azoalkanes is more significantly diminished at the lower (entries 6/3, 12/9, 18/15, 23/20, and 28/25 at −75 °C) than at the higher (entries 5/1, 11/7, 17/13, 22/19, and 27/24 at ≥20 °C) temperatures. This remarkable dependence of the housane syn/anti ratios on temperature and bridgehead substitution for the various photochemical reaction modes signifies competitive denitrogenation pathways for these azoalkanes, which shall now be scrutinized in terms of the mechanistic options given in Scheme 4.

Discussion

Dependence of the syn/anti-Housane Ratio on Temperature: Singlet Versus Triplet Pathways in the Denitrogenation of the Azoalkanes 1. Our previous study on the denitrogenation of azoalkane **1a** showed that the intersystem-crossing process (isc) dominates at low temperatures; in fact, at the low temperature of −75 °C (entry 3), the α-CN-bond cleavage is completely prevented in the ^{1}(n,π*)-excited state.[7] The results in Table 1 demonstrate that this temperature dependence on the singlet−triplet pathways is a general feature in the photochemical denitrogenation of the cyclopentene-annelated azoalkanes **1**. Thus, the low-temperature direct and the benzophenone-sensitized photolyses of the new derivatives **1b**−**e** exhibit the same behavior as the parent azoalkane **1a** (entries 3/4, 9/10, 15/16, 20/21, and 25/26). Clearly, the same denitrogenation pathway is followed in both photolysis modes, that is, the direct at −75 °C and the sensitized at −40 °C! Under these conditions, as we have shown previously for the parent azoalkane **1a**,[7] the low diastereoselectivity is due to the fact that the α-CN-bond cleavage in the singlet route (low-temperature direct photolysis) is slower compared to intersystem crossing of the singlet-excited ^{1}**1**(n,π*) to its triplet-excited ^{3}1(n,π*) azoalkane. A lower-energy process for isc versus α cleavage has been confirmed in recent calculations on the parent **DBH**.[5,10] In this case, a singlet−triplet crossing region has been located <1 kcal/mol above the ^{1}(n,π*)-excited azoalkane. In contrast, the α-cleavage transition state has been located a few kcal/mol above the same excited-state minimum. Thus, isc takes place spontaneously, and the triplet-excited azoalkane denitrogenates to the planar triplet diradical ^{3}**DR** (Scheme 4). After intersystem crossing to the singlet diradical ^{1}**DR**, the latter cyclizes to the *syn/anti*-**2** housanes; the energy profile of this process is shown in Figure 1. In view of the shallow energy well (<3 kcal/mol[2d,17]) of the planar singlet diradical ^{1}**DR**, fast ring closure affords nearly equal amounts of the syn and anti housanes even at −75 °C; thus, the transition state does not sense the substantial (ca. 6 kcal/mol) energy bias in favor of the anti product. The fact that the *syn*-**2e** housane is preferred in the triplet process of the azoalkane **1e** (entries 25 and 26) suggests that in the transition state for the ring-closure process, the steric repulsions of the annelated cyclopentene ring with the bridgehead phenyl substituents are slightly more effective than with the gem-dimethyl-substituted bridge.

Despite the similar structure of the azoalkanes **1**, the variation of the syn/anti ratio differs with temperature for the direct photolysis: While the syn/anti ratio inverts for azoalkane **1a** (entries 1−3) as the temperature is lowered [more syn at high (+40 °C) and more anti at low (−75 °C) temperature],[7] the anti housane prevails for the **1b**−**d** cases at all temperatures

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(16) To estimate the log *A* values of the azoalkanes **1a** and **1c** in eq 1, a singlet lifetime ($^1\tau$) of 2 ns was used, cf. Adam, W.; Fragale, G.; Klapstein, D.; Nau, W. M.; Wirz, J. *J. Am. Chem. Soc.* **1995**, *117*, 12578−12592.

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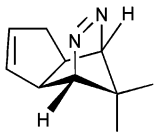
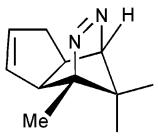
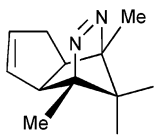
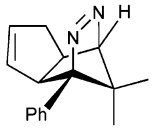
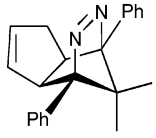
Table 1. Product Studies of the Photochemical Denitrogenation of Azoalkanes **1a**−**e**

entry	azoalkane	mode[a]	temp (°C)	time (min)	convn (%)	product distribution (%)[b] *syn*-**2**	*anti*-**2**
1	 **1a**	direct[c]	40	10	95	62	38
2		direct	-20	15	95	50	50
3		direct	-75	50	72	37	63
4		sensitized[c]	-40	180	38	38	62
5		quenched	20	30	40	61	39
6		quenched	-75	90	<1	-	-
7	 **1b**	direct[c]	40	10	100	35	65
8		direct	-20	15	100	30	70
9		direct	-75	60	100	35	65
10		sensitized[c]	-40	120	100	35	65
11		quenched	20	30	100	34	66
12		quenched	-75	90	75	35	65
13	 **1c**	direct[c]	40	10	95	20	80
14		direct	-20	10	90	22	78
15		direct	-75	30	91	45	55
16		sensitized[c]	-40	180	55	44	56
17		quenched	20	30	100	16	84
18		quenched	-75	90	15	30	70
19	 **1d**[e]	direct[d]	20	10	95	12 (17)	88 (83)
20		direct	-75	30	100	40	60
21		sensitized	-40	120	100	49	51
22		quenched[f]	20	5	70	14	86
23		quenched[f]	-75	90	40	17	83
24	 **1e**[e]	direct[g]	20	10	100	0	100
25		direct	-75	30	100	67	33
26		sensitized	-40	120	58	66	34
27		quenched[f,g]	20	5	60	0	100
28		quenched[f]	-75	80	52	0	100

[a] In d_8-toluene; for the direct and *trans*-piperylene-quenched (1 M) photolyses, the 351-nm (2 W) line of the argon-ion laser was used, for the benzophenone-sensitized (1 M) one, the 333-nm (2.4 W) line. [b] Determined by ^{1}H NMR analysis; normalized to 100% conversion; mass balance ≥95%; error ±5% of the stated values. [c] Within the experimental error, the same syn/anti ratios were obtained at 20 °C. [d] In parentheses is given the syn/anti ratio corrected for the thermal isomerization during the direct photolysis; the corrected value is essentially the same within the experimental error of the NMR analysis. [e] The ^{1}H NMR spectra of the photolyzates were recorded at −50 °C. [f] *cis*-Stilbene was used for the quenched photolysis. [g] At this temperature, the labile *syn*-**2e** housane is thermally isomerized completely to its anti isomer during the direct photolysis (see text).

(Table 1), but the syn isomer dominates at low temperatures for the diphenyl system **1e** (entries 25 and 26). What is structurally different between the azoalkanes **1a** versus **1b**−**e** that may explain this temperature behavior on the syn/anti-housane ratio? Since isc (an entropy-controlled process) is independent of temperature for azoalkanes ($E_{isc} \approx 0$ kcal/mol),[18] the temperature effect must reside in the α-CN-bond cleavage (an enthalpy-controlled process) of the singlet-excited azoalkane[1] **1**(n,π*). Thus, at high temperature, the singlet process (path A in Scheme 4) dominates, at low temperature, the triplet one (path B), that is, isc becomes more competitive with α cleavage. By means of the temperature-dependent fluorescence method (eq 1)[15] employed in this study, the activation energy for the α cleavage of the singlet-excited azoalkane **1a**(n,π*) was 2.08 ± 0.04 kcal/mol and 1.18 ± 0.04 kcal/mol for **1c**(n,π*).[19] Expectedly, the moderately stabilizing methyl group facilitates the breakage of the CN bond in the azoalkane **1c**. By analogy, we infer for the unsymmetrical azoalkane **1b** (not measured) also first cleavage of the CN bond proximate to the methyl-carrying bridgehead position. Similar photochemical behavior should pertain to the

(18) Adam, W.; Nau, W. M.; Sendelbach, J. *J. Am. Chem. Soc.* **1994**, *116*, 7049−7054.

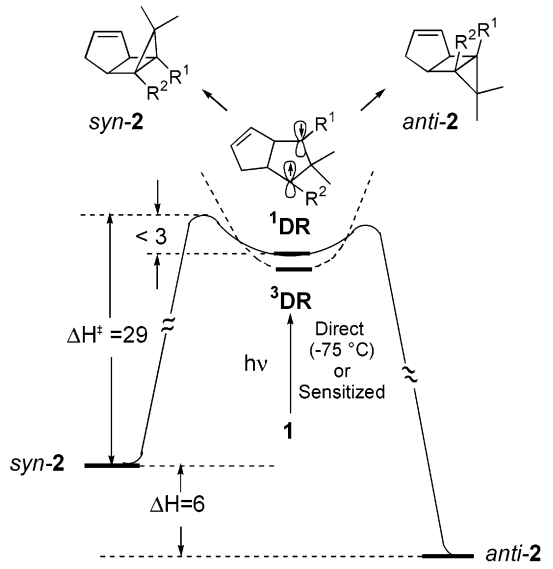


Figure 1. Energy diagram for the syn/anti-housane formation in the thermal syn-to-anti isomerization of the housanes **2** through the singlet diradical **^{1}DR** (solid curve) and in the triplet-sensitized and direct (−75 °C) photochemical denitrogenation of the azoalkanes **1** after isc of the triplet diradical **^{3}DR** (dashed curve) to **^{1}DR**; energy values (kcal/mol) refer to the unsubstituted derivatives **1a** and **2a**.

phenyl derivatives **1d**, **e** (not measurable because of practical problems, cf. Results section); in fact, α cleavage should be more effectively promoted by phenyl stabilization. Consequently, α cleavage should be more facile for all the bridgehead-substituted azoalkanes **1b**−**e** than for the unsubstituted **1a**. It follows that the temperature-dependent syn/anti ratios (Table 1) for the substituted azoalkanes **1b**−**e** should be more similar to one another and different from the unsubstituted **1a**. This is most evident in the direct photolysis, since the anti housane dominates for **1b**−**d** (entries 7, 13, 19, and 24), whereas it is the syn housane in the case of **1a** (entry 1). Be this as it may, this substituent effect does not explain why in the direct photolysis the amount of anti housane depends on the extent and type of bridgehead substitution of the azoalkane (Table 1), namely, **1e**(Ph/Ph) > **1d**(Ph/H) > **1c**(Me/Me) > **1b**(Me/H) > **1a**(H/H), but this shall be addressed in the next section.

The *trans*-piperylene-quenched process also supports the involvement of the triplet pathway at −75 °C (Table 1). For azoalkane **1a**, the denitrogenation is completely inhibited (entries 6 versus 3), which indicates that at this temperature only the triplet pathway is active. For the bridgehead-substituted azoalkanes **1b** (entries 9 and 12), **1c** (entries 15 and 18), **1d** (entries 20 and 23), and **1e** (entries 25 and 28), the quenching effect is not as efficient, as manifested by only partial inhibition of the denitrogenation even at −75 °C. As already stated in the preceding paragraph, some denitrogenation takes place in the singlet channel because of enhanced CN cleavage by stabilization of the incipient radical center on account of the bridgehead substituent such that the isc process is less effective.[18] The lower activation energy for the dimethyl derivative **1c** ($E_a \cong 1.2$ kcal/mol) compared to the unsubstituted **1a** ($E_a \cong 2.1$ kcal/mol) is in accord with enhanced α cleavage in the azoalkane ^{1}(n,π*)-excited state.

Dependence of the syn/anti-Housane Ratio on Bridgehead Substitution: Enhancement of the anti Diastereomer through the Mass Effect (Inertia) and Steric Hindrance in the Inversion Process. In the previous section, it was shown that the extent and type of substitution at the bridgehead position of the azoalkanes **1a**−**e** produces only minor changes in the syn/anti ratio (entries 4, 10, 16, 21, and 26) of the triplet process (path B in Scheme 4). In fact, nearly the same amounts of syn and anti housanes are formed. The same is not the case for the singlet process (path A), especially at the moderately high temperatures (≥20 °C), at which the triplet pathway is negligible compared to α cleavage. The syn/anti product data under these conditions disclose a significant dependence on the extent and type of bridgehead substitution (Table 1). The amount of anti product follows the order **1e**(Ph/Ph) > **1d**(Ph/H) > **1c**(Me/Me) > **1b**(Me/H) > **1a**(H/H), which spans a range in the quantity of anti isomer from 100% for **1e**(Ph/Ph) to only 38% for **1a**(H/H). Thus, disubstitution is more effective than monosubstitution and the phenyl more than the methyl group in promoting the formation of anti housane. Most significant, the amount of anti product in the direct photolysis at ≥20 °C is substantially higher than for the triplet process, except **1a**.

An impressive case is the diphenyl derivative **1e**, for which the syn/anti selectivity changes from 0:100 at 20 °C (entry 24) to 67:33 at −75 °C (entry 25) in the direct photolysis, that is, from complete retention (stereochemical memory) to moderate inversion. In view of the thermal lability of the *syn*-**2e** housane, the pertinent question was whether the *syn*-**2e** was not detected because of thermal isomerization under the direct photolysis conditions at 20 °C or whether it was not formed at all. As control experiment, the quenched photolysis was conducted at −75 °C (entry 28) to assess whether the syn isomer is formed or not in the direct photolysis of **1e** at the elevated temperature of 20 °C (entry 24). Also under these conditions, the syn/anti ratio is 0:100 and again no *syn*-**2e** housane was observed. However, had the *syn*-**2e** housane been formed, it should have survived for low-temperature NMR-spectral detection, as in the direct (−75 °C) and sensitized (−40°C) photolyses (entries 25 and 26) of **1e**. Thus, in the quenched photolysis at −75 °C, the triplet pathway is efficiently inhibited (no syn housane) and only the singlet process operates, to give exclusively anti housane. We contend that the lack of observing the syn housane in the direct photolysis at 20 °C (entry 24) is not due to facile thermal isomerization to its anti isomer at this temperature, but that the syn housane is not formed under these conditions.

The following mechanistically pertinent questions arise: Why do the substituted derivatives **1c**−**e** afford a higher amount of the anti diastereomer than the unsubstituted **1a**? Why is for these azoalkanes significantly more anti housane formed in the direct photolysis than in the triplet-sensitized one? As already pointed out in the Introduction, new computational studies[10] on the parent **DBH** indicate that the axial and equatorial conformations of the *exo*-configured singlet diazenyl diradical σ,σ-**^{1}DZ** intervene in the denitrogenation of the ^{1}(n,π*)-excited azoalkane

(19) The previous E_a value of 3.6 kcal/mol obtained for the azoalkane **1a** from the kinetic analysis of the temperature-dependent syn/anti product distribution is significantly higher than the present value of 2.08 kcal/mol, determined by the temperature-dependent fluorescence method. This difference may be rationalized in terms of solvent effects since d_8-toluene was used in the product-distribution study, while methylcyclopentane was employed in the fluorescence measurements. It is known that solvents affect the E_a values determined by fluorescence (ref 15b). Furthermore, fluorescence quenching through solvent-assisted radiationless deactivation by C−H bonds is expected to be more effective for the aliphatic solvent methylcyclopentane, cf. Nau, W. M.; Adam, W.; Scaiano, J. C. *Chem. Phys. Lett.* **1996**, *253*, 92−96.

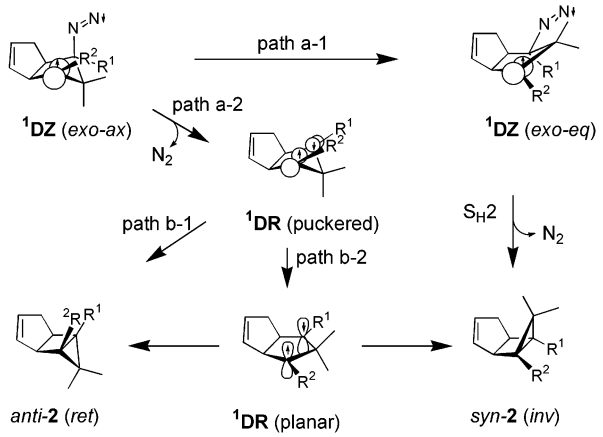
(Scheme 2). This constitutes the pivotal product-branching point to rationalize the preferred formation of inverted housane in the direct photolysis of **DBH** (Scheme 3). We infer that this theoretically based mechanistic scenario also applies to the bridgehead-substituted, cyclopentenyl-annelated DBH-type derivatives **1a**−**e** and accounts for the observed syn/anti-housane ratios (Table 1) in their direct photolysis (path A in Scheme 4); however, no computations are available as yet on these structurally more complex azoalkanes.

As to the fate of the ^{1}**DZ** transient, the two mechanistic pathways in Scheme 1 shall be considered: On one hand, the experimentally[7,11] and theoretically[10] established conventional S_H2 process may take place to afford exclusively the inverted housane *syn*-**2**, in which the N_2 departure is concomitant with the ring inversion by backside attack of the unpaired electron in the carbon-centered 2p orbital; on the other hand, in competition, a nitrogen-free ^{1}**DR** species may be involved to generate both the syn and anti products. For a thermally equilibrated, planar ^{1}**DR** intermediate, the energy diagram in Figure 1 provides a detailed account of the housane formation. In view of the shallow (<3 kcal/mol) potential energy well for the planar singlet diradical ^{1}**DR**, essentially equal amounts of the syn- and the anti-housane **2** are expected. Such a planar ^{1}**DR** species is generated through isc of the long-lived,[20] thermally equilibrated, planar triplet diradical ^{3}**DR** and it follows that the syn/anti ratio for the planar ^{1}**DR** should be that given for the nitrogen-free ^{3}**DR** of the triplet process (path B in Scheme 4).[21,22] It is remarkable that the ring closure of the ^{1}**DR** species is essentially independent of the extent and type of bridgehead substitution (entries 4, 10, 16, 21, and 26). This lack of stereoselectivity clearly manifests that the mass effect of the bridgehead substituents and their steric interactions are negligible when a thermally fully equilibrated, planar ^{1}**DR** diradical intervenes.

The experimental facts for the singlet process (path A in Scheme 4) display a definite effect on bridgehead substitution in that the amount of anti housane follows the order **1e** > **1d** > **1c** > **1b** > **1a** (entries 1, 7, 13, 19, and 24). More importantly, in the azoalkanes **1c**−**e**, the amount of anti diastereomer for the singlet process exceeds significantly that of the triplet one (entries 13 vs 16, 19 vs 21, and 24 vs 26). None of the mechanisms in Scheme 1 explain these unprecedented results. Evidently, there must exist an additional pathway for the ^{1}**DZ** transient to generate the anti housane (dashed arrow from ^{1}**DZ** to *anti*-**2** in Scheme 4). This pathway is promoted by bridgehead substituents, the phenyl is more effective than the methyl group, and double more than single substitution!

Inspection of molecular models reveals that during the ^{1}**DZ** (*exo-ax*)-to-^{1}**DZ** (*exo-eq*) inversion process along the ring-inversion (S_H2) trajectory, the gem-dimethyl group must move past the bridgehead substituents to afford the syn housane. This process is expectedly more difficult the heavier and the larger the substituent at the bridgehead, that is, Ph > Me > H and double more than single substitution. Thus, the S_H2 mode of inversion is encumbered by bridgehead substituents through the mass effect and steric interactions, as manifested by the fact that proportionally more *anti*-**2** housane results in the observed order **1e**(Ph/Ph) > **1d**(Ph/H) > **1c**(Me/Me > **1b**(Me/H) > **1a**(H/H). For the diphenyl derivative **1e**, these synergetic effects are so dominant that the anti housane is the exclusive product.

Scheme 5



In Scheme 5, we provide the mechanistic rationale for these unusual results (Table 1) in terms of the transient diazenyl diradical ^{1}**DZ**, in analogy to the computed[5,10] reaction coordinate for the parent **DBH** (Scheme 2), and its stereochemical implications (Scheme 3). We propose that initially the *exo-axial* diazenyl diradical ^{1}**DZ**(*exo-ax*), formed by decay through the conical intersection, carries sufficient energy to transform dynamically (path a-1) to the *exo-equatorial* conformation ^{1}**DZ**(*exo-eq*), that is, prior to thermal equilibration; subsequently, the latter loses N_2 by backside attack to afford inverted housane *syn*-**2**(*inv*) along the S_H2 trajectory. Alternatively, denitrogenation of ^{1}**DZ**(*exo-ax*) to generate initially the puckered cyclopentanediyl diradical ^{1}**DR**(puckered) competes (path a-2) with the conformational change to ^{1}**DZ**(*exo-eq*) along path a-1. The ^{1}**DR**(puckered) transient subsequently either cyclizes directly (path b-1) to the retained (stereochemical memory) housane *anti*-**2**(*ret*) or conformationally relaxes (path b-2) to the planar nitrogen-free diradical ^{1}**DR**(planar). The latter, that is, the intermediate proposed to be formed from the planar triplet diradical ^{3}**DR** (cf. Scheme 4) on intersystem crossing, is destined to afford essentially equal amounts of *anti*-**2**(*ret*) and *syn*-**2**(*inv*) housanes (Figure 1), as manifested by the product data for the triplet process (entries 3, 10, 16, 21, and 26) in Table 1.

An alternative mechanism would be to suppose that the singlet diazenyl diradical ^{1}**DZ**(*exo-ax*) cyclizes to a vibrationally excited azoalkane. The latter thermally expels N_2 concertedly to generate a nonstatistical nitrogen-free ^{1}**DR** diradical, which on account of dynamic effects favors inversion to the syn housane, the pathway reported for the thermolysis of DBH.[8] If this were so, we would expect more cyclization of the ^{1}**DZ**(*exo-ax*) to its azoalkane in a more viscous solvent and, thus, more syn housane (inversion) should be formed. Our recent results for the dimethyl derivative **1c** disclose, however, that with increasing viscosity the extent of inversion decreases.[11e] On the basis of these

(20) Adam, W.; Grabowski, S.; Wilson, R. M. *Acc. Chem. Res.* **1990**, *23*, 165−172.

(21) Buchwalter, S. L.; Closs, G. L. *J. Am. Chem. Soc.* **1979**, *101*, 4688−4694. In this seminal work, the energy diagram for intersystem crossing of the triplet cyclopentanediyl diradical to its singlet species was proposed as an essential feature for the generation of the bicyclo[2.1.0]pentane product. At very low temperatures (<20 K) under matrix isolation, the triplet diradical may cyclize directly to the bicyclopentane by tunneling instead of intersystem crossing. This pathway does not apply to the substituted triplet diradicals ^{3}**DR** derived from the azoalkanes **1** at the elevated temperatures (>20 °C) of the triplet-sensitized photolysis, as unequivocally stated by Buchwalter and Closs in the citation, "The unambiguous observation of tunneling in organic reactions is rare. While in the reaction described here tunneling is the sole pathway at temperatures below 20 K, its contribution at room temperature of course is negligible (~1 part in 10^{11})."

(22) Sponsler, M. B.; Jain, R.; Coms, F. D.; Dougherty, D. A. *J. Am. Chem. Soc.* **1989**, *111*, 2240−2252.

experimental results, we argue that dynamic effects[8] are not detectable in the photodenitrogenation of azoalkanes.[11] Additionally, recent computations[5,10] indicate that the n,π*-singlet-excited DBH generates initially the **^{1}DZ**(*exo-ax*) diradical (Scheme 3), which prefers to denitrogenate rather than reclose to DBH through its endo-configured conformer. This is consistent with the reported quantum yield of ca. 100% for nitrogen loss.[23] In analogy, for the present set of azoalkanes **1** (Scheme 5), the intermediary **^{1}DZ**(*exo-ax*) diradical does not have enough time to reclose to a "hot" azoalkane and afford on thermolysis inverted housane through dynamic effects.[8]

It remains to rationalize the observed syn/anti ratios in Table 1 for the direct photolysis of the azoalkanes **1a**−**e** in terms of the influence of the bridgehead substituents on the two bifurcation steps in Scheme 5, namely, paths a-1/a-2 and paths b-1/b-2. As already mentioned, two factors influence the conformational changes: These are the mass effect (inertia) and steric hindrance (size), both follow the order Ph > Me > H. Thus, the larger mass imparts a drag (inertia) on the bridgehead substituent during the inversion, whereas the larger size imposes a higher steric barrier in moving the bridgehead substituent past the gem-dimethyl bridge; both expectedly slow the conformational changes.

We shall first scrutinize the two extreme cases, which are the unsubstituted derivative **1a** (entry 1) and the diphenyl case **1e** (entry 24). For **1a**(H/H), both the mass drag and the steric hindrance are minimal on the conformational change along path a-1 and most of the singlet-state denitrogenation proceeds by the S_H2 mechanism to afford mainly inverted housane *syn*-**2a**(*inv*). Since substantial amounts of retained housane *anti*-**2a**(*ret*) are produced, denitrogenation along path a-2 must take place, but beyond this point it is difficult to assess even qualitatively what happens stereochemically, because no information is available on the relative importance of the path b-1 versus path b-2 in the subsequent bifurcation step. If we assume that all of the **^{1}DR**(puckered) relaxes to **^{1}DR**(planar) along path b-2 (no memory effect), ca. one-third of the direct photolysis goes through the S_H2 process and ca. two-thirds through the thermally equilibrated **^{1}DR**(planar) diradical. In contrast, the stereochemical analysis of the **1e**(Ph/Ph) case is straightforward, since only the retained housane *anti*-**2e**(*ret*) is obtained, that is, complete stereochemical memory. In this case, both the mass and steric factors operate so efficiently that only the a-2 and b-1 paths are pursued by the respective diradicals **^{1}DZ**(*exo-ax*) and **^{1}DR**(puckered); the conformational changes in the a-1 and b-2 paths are too slow to compete with the a-2 and b-1 paths.

An informative case is the monomethyl derivative **1b**. Its unsymmetrical ^{1}(n,π*)-excited state has two options to undergo CN-bond cleavage to afford the **^{1}DZ** transient, for which the 2p orbital is centered on the methyl-substituted or on the unsubstituted bridgehead carbon atom. The former is subject to a mass effect exerted by the methyl group, the latter is not. Although there will be an energy bias in favor of the CN-bond homolysis next to the substituted bridgehead site in the excited state because of methyl stabilization of the incipient carbon-radical center, if both CN bonds were to cleave equally likely, the syn/anti ratio for the monosubstituted azoalkane **1b**(Me/H) would be expected to be between those of the symmetrical ones **1a**(H/H) and **1c**(Me/Me), namely, 41:59, as computed from the entries 1 and 13 (Table 1). This is remarkably close (essentially the same within the experimental error) to the experimental value of 35:65 (entry 7) and corroborates the validity of the inertia effect of the bridgehead substituent. For the monophenyl derivative **1d**(Ph,H), phenyl stabilization of the radical center is so effective that the excited-state homolysis of the adjacent CN bond dominates to such an extent that the inversion process is almost completely suppressed through the mass effect, but also by steric hindrance, and the anti-housane product is favored by far (entry 19). The synergetic interplay between the mass effect (inertia) and steric interactions (size) allows to rationalize the dominance of the anti-housane diastereomer in the direct photolysis of the azoalkanes **1b**−**e** (Table 1).

Conclusion

In this study, we have established that the temperature-dependent competition between the singlet and triplet pathways in the denitrogenation of the n,π*-excited cyclopentene-annelated azoalkanes **1** is a general feature. We have also demonstrated an unprecedented influence of the apparently innocuous bridgehead substituent on this process, in that *anti*-**2** housane is formed more effectively by phenyl versus methyl substituents and by double versus single substitution. The mass effect (inertia) of the bridgehead substituent and its steric hindrance with the gem-dimethyl-substituted methylene bridge encumber the formation of the syn housane through the inversion process (S_H2 pathway). Instead, the transient **^{1}DZ** diradical affords proportionally more of the anti stereoisomer (retention) through the puckered nitrogen-free **^{1}DR** species (memory effect).

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Supporting Information Available: Experimental and computational details (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

JA026321N

(23) Solomon, B. S.; Thomas, T. F.; Steel, C. *J. Am. Chem. Soc.* **1968**, *90*, 2249−2258.