

Homolytic Substitution (S_H2) versus Triplet Diradical (ISC) in the Photochemical Denitrogenation of a DBH Azoalkane: Temperature-Dependent *syn/anti* Diastereoselectivity as a Mechanistic Probe for the Doubly Inverted Housane

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Since the discovery of the preferred formation of the doubly inverted bicyclo[2.1.0]pentane (housane) product in the thermal and photochemical denitrogenation of diazabicyclo[2.2.1]heptene (DBH), the elucidation of the mechanism has been a persistent controversy.¹ The denitrogenation of the cyclopentene-annulated DBH derivative **1** serves as an example (Scheme 1), which is the subject of this mechanistic study. Experimental¹ and theoretical² evidence favor the intervention of the diazenyl diradical (DZ); thus, the initially proposed homolytic substitution process (path A),^{1a} in which the unpaired electron in the carbon-centered 2p orbital displaces N₂ by back-side attack (S_H2), is more likely than the successive CN cleavage by way of the nitrogen-free diradical (³DR) to rationalize the double inversion (path B).

An evident exception to the formation of the doubly inverted product is the recently³ observed exclusive generation of the *anti*-configured, cyclopentene-annulated housane in the photolysis of the corresponding azoalkane **1** with phenyl substituents at the bridgehead positions; not even traces of the *syn* diastereomer were detected. In view of the higher strain energy in the *syn* diastereomer (ca. 6 kcal/mol by AM1³), it may be argued that severe buttressing between the cyclopentene and the dimethylcyclopropane rings prevents the ring closure to the *syn* product. That this simple rationale does not apply is demonstrated presently since, for housane **2**, the *syn* diastereomer is obtained in the photolysis of the azoalkane **1**. We provide herein unequivocal experimental support that the S_H2 process (path A) is the prevalent reaction channel at elevated temperatures for the generation of the sterically encumbered *syn* product, while at low temperatures the triplet pathway (path B) operates and loss of the *syn* selectivity is observed.

The known azoalkane **1** was prepared according to the Hünig route.³ Solutions in toluene-*d*₈ were purged with Ar gas and irradiated at the conditions specified in Table 1 (footnote b).

The direct photolysis of the azoalkane **1** at 20 °C afforded, as expected,³ the *anti*-**2** housane, but additionally the ¹H NMR

Scheme 1

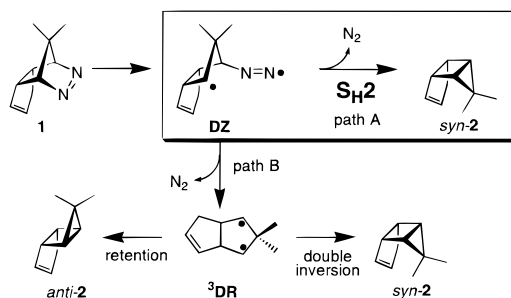


Table 1. Product Studies of the Azoalkane **1** Photolyses

entry	photolysis conditions ^b	temp (°C)	time (min)	convn (%)	product distribution (%) ^a	
					<i>syn</i> - 2	<i>anti</i> - 2
1	direct	60	10	82	67	33
2	direct	40	10	95	62	38
3	direct	20	15	84	60	40
4	direct	-8	10	71	53	47
5	direct	-20	15	95	50	50
6	direct	-30	20	87	45	55
7	direct	-50	25	50	41	59
8	direct	-75	50	72	37	63
9	sensitized	60	120	97	39	61
10	sensitized	-75	180	38	38	62
11	quenched	20	30	40	61	39
12	quenched	-20	45	69	56	44
13	quenched	-30	45	31	54	46
14	quenched	-75	90	<1	—	—

^a Determined by ¹H NMR analysis; normalized to 100% conversion; error $\pm 3\%$ of the stated values. ^b In toluene-*d*₈; for the direct and *trans*-piperylene-quenched (1 M) photolyses, the 351-nm (2 W) line of the argon ion laser was used, and for the benzophenone-sensitized (1 M) one, the 333-nm (2.4 W) line was used.

spectrum of the photolysate revealed a new product whose spectral data are very similar (entry 3). This new product was assigned to the *syn*-**2** diastereomer on the basis of characteristic chemical shifts and NOE effects (cf. Supporting Information). This assignment was confirmed by thermal isomerization of the labile *syn* diastereomer quantitatively to the *anti* one at 90 °C. Such *syn*-to-*anti* isomerization has been reported for other housanes,⁴ and as expected in view of the lower energy (ca. 6 kcal/mol by PM3) for the *anti* diastereomer, this persistent housane should accumulate on thermal equilibration. The activation parameters for the *syn*-to-*anti* isomerization of the housane **2** were determined to be $E_a = 29 \pm 2$ kcal/mol and $\log A = 12.6 \pm 0.9$ s⁻¹; thus, at 90 °C, the half-life of *syn*-**2** is ca. 8 h.

The *syn/anti* ratio in the azoalkane **1** photolysis was examined as a function of temperature. Much to our surprise, the *syn/anti* ratio increased with increasing temperature, i.e., 37:63 at -75 °C (entry 8) versus 67:33 at 60 °C (entry 1). In view of the facile thermal *syn*-to-*anti* isomerization of housane **2**, at the higher temperature the opposite trend would have been expected. Something mechanistically unusual is happening in the photolysis of the azoalkane **1** to account for the fact that the more labile *syn*-**2** housane is formed preferably at the higher temperature.

The benzophenone-sensitized photolysis was carried out to assess the temperature dependence of the *syn/anti* ratio for the triplet process. Contrary to the direct photolysis, the results for this photolysis process (entries 9 and 10) show that, between 60 and -75 °C, the *syn/anti* ratio is, within the error, ca. 40:60. Mechanistically most indicative is the fact that the *syn/anti* ratio of housane **2** for the triplet process is identical to that observed for the direct photolysis at -75 °C (entries 8 and 10). This coincidence in the *syn/anti* ratios implies that, for the low-temperature

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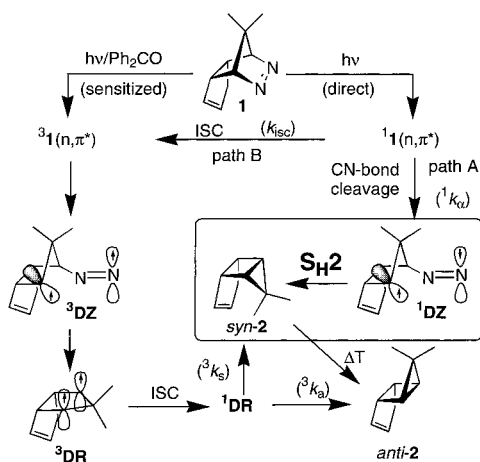
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Scheme 2



direct photolysis, the triplet-state process is the only one which operates. Indeed, that this is the case was confirmed by conducting the direct photolysis of the azoalkane **1** in the presence of *trans*-piperylene ($E_T = 59$ kcal/mol).^{5a} The consumption of azoalkane **1** at -75 °C (entry 14) is completely inhibited, i.e., <1% conversion even after 90 min of irradiation, such that a *syn/anti* ratio was immeasurable. Already at 20 °C (entry 11), the triplet quenching is ineffective since the same *syn/anti* ratio of 60:40 as for the direct photolysis (entry 3) was obtained, while at ca. -30 °C (entry 13) it becomes significant, as reflected by the reduced conversion and a shift of the *syn/anti* ratio toward that for the triplet-sensitized photolysis (entries 9 and 10). The lack of triplet quenching by *trans*-piperylene at the elevated temperature reflects the low lifetime of the azoalkane triplets due to efficient α cleavage under these conditions. Indeed, the fact that no phosphorescence could be observed for this azoalkane^{5a} signifies that its triplet lifetime must be subnanoseconds at elevated temperatures (>20 °C) and, thus, its quenching inefficient.

The mechanism in Scheme 2 accounts for all the observations in Table 1. At the higher temperatures (>20 °C), the *syn-2* housane is the main photoproduct, generated from $^1\mathbf{1}(n, \pi^*)$ along path A through the singlet diazenyl diradical $^1\mathbf{DZ}$, followed by $S_{\text{H}2}$ -type extrusion of N_2 . Intersystem crossing (ISC) competes with α cleavage in the singlet-excited azoalkane $^1\mathbf{1}^*$ during the direct photolysis, and the temperature dependence of the *syn/anti* ratio reflects this product branching.

The kinetic analysis of the temperature-dependent competition in the direct photolysis (Scheme 2) leads to the expression in eq 1 in terms of the $[\text{syn}]/[\text{anti}]$ ratio, in which $^3k_s/{}^3k_a$ is given by the ${}^3[\text{syn}]/{}^3[\text{anti}]$ ratio for the triplet photolysis. On solving for ${}^1k_\alpha/k_{\text{ISC}}$, making appropriate substitution, and after taking the logarithm, eq 2 is obtained.^{5b}

$$\frac{[\text{syn}]}{[\text{anti}]} = \frac{{}^3k_s}{{}^3k_a} + \frac{{}^1k_\alpha(1 + {}^3k_s/{}^3k_a)}{k_{\text{ISC}}} \quad (1)$$

$$\ln\left(\frac{{}^1k_\alpha}{k_{\text{ISC}}}\right) = \ln\left(\frac{[\text{syn}]/[\text{anti}] - {}^3[\text{syn}]/{}^3[\text{anti}]}{{}^3[\text{syn}]/{}^3[\text{anti}] + 1}\right) = \ln\frac{{}^1A_\alpha}{A_{\text{ISC}}} - \frac{{}^1E_\alpha - E_{\text{ISC}}}{R} \frac{1}{T} \quad (2)$$

From the experimental product ratios $[\text{syn}]/[\text{anti}]$ for the direct irradiation (entries 1–8) and the ${}^3[\text{syn}]/{}^3[\text{anti}]$ ratio for the benzophenone-sensitized one (entries 9–10), an Arrhenius plot

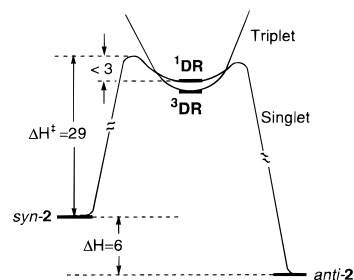


Figure 1. Energy diagram (in kcal/mol) for the *syn-to-anti* isomerization.

affords the linear relation $\ln({}^1k_\alpha/k_{\text{ISC}}) = (5.6 \pm 0.8) - (1840 \pm 260)T^{-1}$ ($r^2 = 0.952$). Since ISC is temperature independent ($E_{\text{ISC}} \approx 0$ kcal/mol),^{5b} the slope of this plot gives ${}^1E_\alpha = 3.6 \pm 0.5$ kcal/mol for the α cleavage process of the $^1\mathbf{1}(n, \pi^*)$. This ${}^1E_\alpha$ value is significantly higher than that for the parent DBH (ca. 0.3 kcal/mol), about as high as that for the related norbornene-annulated DBH (ca. 3.2 kcal/mol), and substantially lower than that for DBO derivatives (6–11 kcal/mol).^{5b} Thus, the apparent anomaly that at higher temperatures the thermally labile *syn* product is favored may be readily resolved in terms of the competition between the $S_{\text{H}2}$ process (path A, favored at high temperature) and spontaneous ISC (path B, favored at low temperature) for the singlet-excited azoalkane **1** in Scheme 2. The loss of *syn* selectivity at low temperatures derives from spontaneous ISC along path B. Subsequent CN bond cleavage generates the triplet diazenyl diradical (${}^3\mathbf{DZ}$), followed by N_2 extrusion to the triplet diradical ${}^3\mathbf{DR}$, which affords a 40:60 mixture of *syn/anti* housanes **2** through its singlet diradical ${}^1\mathbf{DR}$ after ISC. The fact that a ca. 50:50 *syn/anti* mixture is obtained requires a planar conformation of ${}^3\mathbf{DR}$.⁶

What is puzzling, however, about the *syn/anti* ratios for the azoalkane **1** in Table 1 is the fact that, for the triplet-state process, about equal amounts of both diastereomers are formed. Since triplet diradical ${}^3\mathbf{DR}$ (Scheme 2) possesses a planar conformation, the strong steric bias (ca. 6 kcal/mol by PM3) in favor of the *anti* isomer should exclusively generate the latter, as observed in the thermal *syn-to-anti* isomerization. The ISC step (${}^3\mathbf{DR} \rightarrow {}^1\mathbf{DR}$) provides the clue for understanding this (Figure 1). In view of the expected early transition state, as the triplet diradical ${}^3\mathbf{DR}$ intersystem-crosses, it drops into the energy well of the singlet diradical ${}^1\mathbf{DR}$ and subsequently cyclizes to the 40:60 mixture of housane **2**.

In summary, we have provided experimental evidence that, as the temperature is raised, the $S_{\text{H}2}$ gains significance in the N_2 extrusion of ${}^1\mathbf{DZ}$ to generate doubly inverted *syn-2* from ${}^1\mathbf{1}(n, \pi^*)$. These results are consistent with Carpenter's dynamic model.^{1f} The loss of *syn* selectivity at low temperatures is due to efficient intersystem crossing in the singlet-excited azoalkane to afford the planar, nitrogen-free triplet diradical (${}^3\mathbf{DR}$), which unselectively ring-closes.

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Supporting Information Available: Experimental details and characterization data for *syn-2* housane and *anti-2* housane (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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