Stereoisomerization and Homolytic Decomposition of Cis and Trans Bridgehead Diazenes[1,2]

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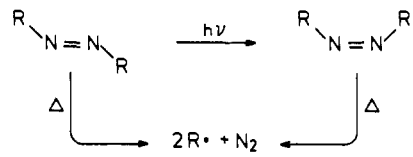
Abstract: For a large series of bridgehead azo compounds, activation parameters for their homolytic decomposition and their cis–trans isomerization reactions are reported. In addition experimental heats of isomerization were obtained and compared with molecular mechanics calculations. It is concluded from a Bell–Evans–Polanyi plot that, in contrast to a previously made assumption, no change in mechanism within this series of *trans*-azo decompositions is occurring. The slope of the correlation as well as the Ramsperger criterion supports the hypothesis of a two-bond concerted decomposition pathway. Changes in $\Delta S^{\ddagger}$, however, also have a major influence on the rates of these reactions. In similar fashion, evidence for a uniform mechanism for all cis–trans isomerizations within this series was obtained. Structure reactivity relationships strongly support the frequently discussed inversion mechanism, the transition state of which, however, has not a semilinear geometry but is closer to the *cis*-azo structure on the reaction coordinate. Engel's hypothesis of isoenergetic transition states for the homolytic decomposition of *cis*- and *trans*-azoalkanes is not supported by our data in this series.

Aliphatic azo compounds are an important class of free radical initiators. Their thermal and photochemical decompositions into radicals have been the subject of extensive investigations.[3,4] It was recognized only recently that the latter process is characterized by the fast thermal decomposition of the photochemically formed cis isomer.[4] The homolytic decomposition of both isomers is an endothermic process. Their rates increase parallel with the electronic stabilization by substituents of the radicals being formed[3-5] (Scheme I).

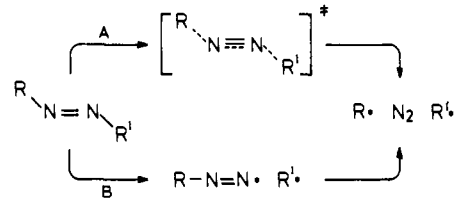
Over the past 50 years, two alternative mechanisms have been presented for the thermal decomposition reaction of *trans*- and *cis*-azoalkanes:[3-6] a concerted two-bond cleavage with extrusion of nitrogen (A) and a two-step nonconcerted process via diazenyl radical intermediates (B)[3,4,7-15] (Scheme II).

To distinguish between routes A and B, structure–reactivity relationships, in particular the effects of strain[4] and substituent groups[6b] on the rates of decomposition of symmetrical (R = R′) and unsymmetrical (R ≠ R′) azoalkanes,[4,6] have been used. Additional information about the reaction mechanism was obtained by isotope effects,[8] CIDNP,[9] thermochemistry,[10] pressure effects on rates,[11] and theoretical calculations and trapping experiments.[12-15]

Scheme I



Scheme II



Until recently there seemed to be general agreement[4,16] that "azoalkane thermolysis may proceed by a continuum of mechanisms between (A) and (B); the more unsymmetrical the azo compound, the more unsymmetrically it cleaves".[4] It has also been suggested that not only the photochemical but also the thermal decomposition of *trans*-azo compounds proceeds via cis isomers.[12a,17]

Recently, diazenyl radicals have been postulated more generally as intermediates, not only for the decomposition of certain symmetrical *cis*- or *trans*-azoalkanes but also for the cis–trans isomerization.[11a,b] On the basis of $\Delta V^{\ddagger}$ data, Neuman and co-workers claimed[11b] that both the thermal deazatization and isomerization reactions of symmetrical *cis*-azo-1-adamantane and *cis*-azo-1-methylcyclopentane proceeded via intermediate diazenyl radicals.[11a] Concerning the isomerization reaction, we questioned this claim when the activation volume for the isomerization of *cis*-1-azobicyclo[2.2.1]heptane became known[11c] and it agreed with that of 1-azoadamantane. The former isomerization reaction proceeds quantitatively and definitely does not go via diazenyl radicals.[11c,d,18]

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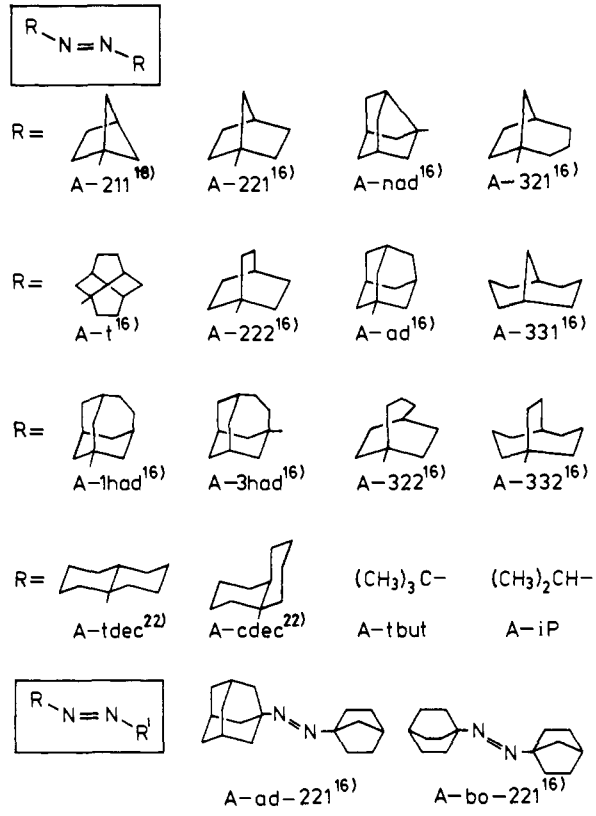
Chart I

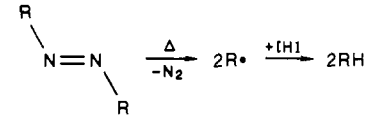


Neuman's claim[11a] of a two-step cleavage reaction of *cis*-azoalkanes was supported, on the other hand, by MNDO calculations for azoethane, which seem to support ethyldiazenyl radicals as intermediates of its decomposition reaction. We have questioned the significance of these calculations because they require a hardly acceptable activation barrier of 10 kcal·mol^{-1} for the dimerization of the radical pair involved.[11c,12b] Apparently, this is a result typical for MNDO calculations, which generally provide too low values for the heats of formation of radicals, e.g., ethyl. Therefore we consider the MNDO-derived activation energies for the dimerization of Et$^{\bullet}$ and $EtN_2^{\bullet}$ to be unreliable.[19]

Engel demonstrated that during the cis–trans isomerization of certain unsymmetrically substituted (α,α-dimethylallyl)azoalkanes, "turnaround" *trans*-azo products, i.e., (γ,γ-dimethylallyl)azoalkanes, were also formed.[14] This is support for an intermediate diazenyl dimethylallyl radical pair and its cage recombination, but it does not require this to be the main reaction path available for cis–trans isomerization. Especially during the isomerization of the symmetrical 1,2-bis(1,1-dimethyl-2-propenyl)diazene, no turnaround *trans*-azoalkanes could be detected.

We decided to address the problem of determining if diazenyl radicals are intermediates during isomerization of symmetrical azoalkanes by a thermochemical/kinetic approach. A diazenyl alkyl radical pair formed in the rate-determining step of the isomerization requires decreasing activation barriers with increasing radical stability of the alkyl group. However, it is not sufficient just to compare kinetic data of cis–trans isomerization, because one has to correct for the different ground-state energies of the cis isomers. A far better reference point for comparison are strainless *trans*-azoalkanes. Therefore the activation barriers for trans–cis isomerization are much more meaningful than the ones for cis–trans stereomutation. Consequently, the heats of isomerization, ΔH_{isom}, ought to be measured. So far only few values, most of them determined in the solid state, are known.[18]

Scheme III



Our technique[2] to measure ΔH_{isom} in solution avoids all the problems associated with solid-state isomerization and will be applied here.

Knowing the ΔH_{isom} would also allow us to address the question of whether the transition states of the thermal decompositions of *cis*- and *trans*-azoalkanes are isoenergetic, as proposed by Engel.[18] Additionally, transition-state energies of the thermal decomposition and trans–cis isomerization can be compared.

For obtaining more detailed information about the reaction hypersurface of thermal azo reactions, bridgehead diazenes[11c,16,18] are particularly suited because of the high thermal stability of the cis isomers. Some of the *cis*-azo isomers (e.g., *cis*-A-211 and *cis*-A-221; see Chart I for explanation of A-211 designation) are stable at room temperature and isomerize cleanly to the trans isomers at higher temperature. Others, e.g., *cis*-A-ad and *cis*-A-222, are less stable, and the cis–trans isomerization is accompanied by homolytic decomposition. In this competition the homolytic pathway is favored not only when better stabilized radicals are generated but also by bulky groups.[20] Using bridghead azoalkanes additionally avoids problems associated with azo–hydrazone tautomerism.

In order to test our working hypothesis we decided to synthesize a whole series of known and unknown bridgehead *cis*- and *trans*-azoalkanes and to study them by thermochemical (heats of isomerization) and kinetic (activation parameters) methods. Additionally, we intended to check out the reliability of two azoalkane force fields[21] to predict heats of isomerization of highly strained *cis*-diazenes.

Synthesis and Spectra of Bridgehead Azo Compounds. The syntheses of the bridgehead *trans*-azo compounds, which are discussed in this paper (Chart I), have been reported previously.

The cis isomers were generated from the trans isomers by 350-nm irradiation in pentane or toluene at −35 to 15 °C. They were separated from the trans isomers, which remained present in the photostationary mixture, by filtration–chromatography over basic Al_2O_3 in the same solvents and by elution of the slowly migrating cis isomer with methanol. All operations had to be performed at low temperature. The *cis*-diazenes finally were crystallized in a nonpolar solvent at low temperature in the dark. None of the routine analytical methods were satisfactory for proving the absence of the trans isomer in concentrations less than 5%. Support for the absence of significant amounts of the trans isomers was obtained during the determinations of the heats of isomerization and will be reported below.

The ^{13}C NMR spectra, recorded in the Experimental Section, were characteristic for the bridgehead hydrocarbon residues and could be assigned by off-resonance spectra and spin–echo experiments. The signals of the bridgehead carbons bound to the azo group always had the highest chemical shift (66–83 ppm). No clear diagnostic differences between *cis*- and *trans*-azo compounds were found. For A-t and A-321, different chemical shifts were observed for the meso and D,L diastereomers in the cis but not in the trans series. The mass spectra of the trans isomers all showed the characteristic M^+ peaks, and the R^+ peaks usually had the highest intensity.

Thermal Decomposition of the *trans*-Azo Compounds. The kinetics of the thermal decomposition of the bridgehead *trans*-azo compounds were measured by following the decrease of their concentration with time by quantitative GC as described previously.[16,22] For each compound, four to nine rate constants were determined over a temperature range ≥40 °C. Activation pa-

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Table I. Kinetics (GC) and Products of the Thermal Decomposition of Bridgehead *trans*-Azoalkanes RNNR′ in Mesitylene[g]

compd	n[a]	ΔT[b]	k_{rel}(300 °C)	$\Delta H^{\ddagger}$, kcal/mol	$\Delta S^{\ddagger}$, eu	$\Delta G^{\ddagger}$(300 °C), kcal/mol	yield RH/R′H, %
A-221	4	40	1.0	52.6 ± 0.3	3.2 ± 0.4	50.7	99
A-nad	5	55	9.3	52.7 ± 0.5	7.8 ± 0.8	48.2	90
A-321	5	45	77	52.7 ± 0.6	12.0 ± 1.0	45.9	98
A-t	5	45	83	50.5 ± 0.5	8.3 ± 0.9	45.8	72
A-222[c]	9	45	127	51.9 ± 0.5	11.6 ± 0.8	45.2	95
A-ad	7	42	803	49.0 ± 1.2	10.2 ± 2.2	43.1	79
A-331[16,d]			1353				*e*
A-1had[16,d]	4	30	26×10^3	47.1 ± 1.3	13.8 ± 2.6	39.2	*e*
A-322[16,d]	3	30	33×10^4	42.2 ± 0.3	10.3 ± 0.5	36.3	*e*
A-3had[16,d]	5	35	47×10^5	43.6 ± 2.0	18.0 ± 4.1	33.3	*e*
A-*t*-but[16,d]			62×10^5	42.2 ± 0.3	16.1 ± 0.6	33.0	*e*
A-332[16,d]	4	30	94×10^5	41.6 ± 0.2	15.9 ± 0.5	32.5	*e*
A-c-dec[22,f]	3	20	62×10^5	41.8 ± 0.1	15.4 ± 0.3	33.0	*e*
A-*t*-dec[22,f]	3	20	79×10^5	41.8 ± 0.3	15.9 ± 0.6	32.7	*e*
A-ad-221	6	50	48.4	48.7 ± 0.8	4.1 ± 1.3	46.3	94
A-bo-221	6	48	17.6	51.8 ± 0.9	7.5 ± 1.4	47.5	93
A-*t*-but-221[16,d]	3	25	15.1×10^3	48.3 ± 1.6	14.8 ± 3.0	39.8	

[a] Number of kinetic runs. [b] Temperature range of kinetic runs. [c] Some rates in toluene or tetraline. [d] In benzene. [e] See original literature. [f] In ethylbenzene. [g] For activation parameters of *t*-Bu-N=N-R, see ref 16.

Table II. Isomerization and Decomposition of *cis*-Azoalkanes

cis compd[a]	process[b]	method[c]	n[d]	yield,[e] %	$\Delta H^{\ddagger}$, kcal/mol	$\Delta S^{\ddagger}$, eu	$\Delta G^{\ddagger}$(50 °C), kcal/mol	n'[f]	ΔH_{isom}(cis–trans), kcal/mol
A-211[g]	I	UV		100	30.3	0.8	30.0		−12.7 ± 0.2[o]
A-221	I[g,h]	UV		100	30.9 ± 0.5	12.0 ± 1.3	27.0		
	I	DSC[i]	5	100	31.1 ± 0.9	9.8 ± 2.2	28.0	5	−16.24 ± 0.92
A-nad	I	DSC[i]	5	100	29.9 ± 0.2	9.1 ± 0.5	27.0	4	−17.58 ± 0.40
A-bo-211	I	DSC[i]	10	99.82 ± 0.01	25.5 ± 1.3	2.1 ± 3.6	24.8	10	−21.3 ± 1.1
	I	UV[i]	6		25.6 ± 0.1	3.0 ± 0.2	24.6		
A-ad-221	I	DSC[i]	9	98.54 ± 0.28	26.2 ± 0.4	5.8 ± 1.3	24.4	8	−21.42 ± 0.97
A-t	I	DSC[i]	10	97.28 ± 0.06	26.9 ± 0.6	8.8 ± 1.9	24.1	12	−22.72 ± 0.62
A-ad[g]	I[k]	UV			23.2	3.0	22.2		
	D[k]	UV			28.5	20.5	21.9		
A-321	D + I	DSC[i]	9	94.12 ± 0.81	28.0 ± 0.5	7.9 ± 1.4	25.5		
	I[k]	DSC			27.7 ± 0.5	6.9 ± 1.4	25.4	11	−23.34 ± 1.09
	D[k]	DSC			39.4 ± 1.0	33.3 ± 2.9	28.6		
A-222	I + D	UV[g]			25.9 ± 0.3	9.3 ± 0.9	22.4		
	I + D	DSC[l]	4	92.95 ± 0.24	26.0 ± 0.3	9.1 ± 0.7	23.1		
	I[k]	DSC			25.7 ± 0.3	8.6 ± 0.7	22.9	8	−25.91 ± 0.68
	D[k]	DSC			32.3 ± 1.3	23.0 ± 4.2	24.9		
A-*i*-p[m]	I[k]	UV			32.2	−4.4	33.6		−8[p]
	D[k]	UV			39.9	18.6	33.8		
A-*t*-but	D[n]	UV		0	18.6 ± 1.0	5.6 ± 4	16.9		

[a] See Chart I. [b] I = isomerization, D = decomposition. [c] Kinetic procedure. [d] Number of kinetic runs. [e] Percent trans isomer formed. [f] Number of DSC experiments used for determination of ΔH_{isom}. [g] Results from ref 18 in xylene. [h] For results in other solvents, see ref 26. [i] In mesitylene. [k] Analyzed by temperature-dependent product analysis. [l] In ethylbenzene. [m] "Azo isopropane", results from ref 4 and 30. [n] Results from ref 31 in pentane. [o] Determined in the melt. [p] Estimated in ref 4.

rameters were obtained by the Eyring equation using a nonlinear least-squares program.[23] In all examples the bridgehead hydrocarbons, RH, were analyzed as products in 72–99% (Scheme III). The products are explained via hydrogen abstraction from the solvent (toluene, ethylbenzene, mesitylene, or 1,2,3,4-tetrahydronaphthalene) by the bridgehead radicals.[24] The results are recorded in Table I together with some data from our earlier work.[16]

The increase in rate with increase in size and flexibility of the polycyclic bridgehead groups in Table I is not only due to decreasing activation enthalpies $\Delta H^{\ddagger}$ but likewise to considerably increasing activation entropies $\Delta S^{\ddagger}$. The data follows an isokinetic relationship as seen from the EXNER test:[25]

$$\Delta G^{\ddagger}(400\ ^{\circ}\mathrm{C}) = 1.128\Delta G^{\ddagger}(200\ ^{\circ}\mathrm{C}) - 7.687\ \mathrm{kcal \cdot mol^{-1}} \quad (1)$$

$$(r = 0.997)$$

This relationship is also shown by the fact that a reasonably good linear correlation exists between $\Delta S^{\ddagger}$ and $\Delta G^{\ddagger}$(300 °c).[2]

Kinetics of the Cis–Trans Isomerization. The isomerization kinetics of the *cis*-diazenes were measured either by following the decrease in UV absorption at λ_{max} of the cis isomer[26] at constant temperatures or by analyzing the heat flow in a differential scanning calorimeter[1,27] running a linear temperature program. The DSC curves were evaluated by a computer program[2] providing a base line correction and by analyzing the kinetic reaction order[27] from the shape factor.[28] The shape factor is defined to be the ratio of the areas to the right and to the left of a vertical line going through the peak of the DSC curve. The statistical error of the activation parameters was always small, because of the large number of rate constants (>100) obtainable from the curve. For a more realistic estimate of errors several independent kinetic runs were compared. The agreement of results obtained by the two methods is generally excellent as seen from the data in Table II and from previous work.[1,29]

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(28) Varhegyi, G.; Szekely, T. *Thermochim. Acta* **1982**, *57*, 13.

Table III. Heats of Formation and Heats of Isomerization of Azo Compounds from Force Field Calculations (Snyder Force Field[21b]) and Their Comparison with Experimental Results (kcal/mol)

compd[a]	$\Delta H_f°$(trans)[b]	$\Delta H_f°$(cis)[b]	ΔH_{isom}[b] (cis–trans)	ΔH_{isom}(exp)[c] (cis–trans)	$\Delta H^{\ddagger}$[d] (trans–cis)
A-211	90.6	103.5	−12.9	−12.7 ± 0.2	43
A-221	28.6	45.7	−17.1	−16.2 ± 0.9	47.3
A-nad	25.5	44.3	−18.8	−17.6 ± 0.4	47.5
A-bo-221	16.9	39.4	−22.5	−21.3 ± 1.1	46.9
A-ad-221	7.7	31.3	−23.6	−21.4 ± 1.0	47.6
A-t[e]	18.2	43.4	−25.2	−22.7 ± 1.0[g]	49.6
A-t[f]	18.1	43.9	−25.8		
A-321[e]	7.3	30.4	−23.1	−23.3 ± 1.1[g]	51.0
A-321[f]	7.0	29.8	−22.8		
A-222	6.7	34.9	−28.2	−25.9 ± 0.7	51.6
A-ad	−10.6	17.8	−28.4	−26.1[h]	49.3
A-*t*-but	−8.5	19.5	−28.0	−25.8[h]	

[a] See Chart I. [b] EFF results[21b] in kcal·mol^{-1}. [c] Results from Table II except when stated otherwise. [d] $\Delta H^{\ddagger}$(trans–cis) = $\Delta H^{\ddagger}$(cis–trans) − ΔH_{isom}(cis–trans) in kcal·mol^{-1}. [e] (*R*,*R*) diastereomer. [f] (*R*,*S*) diastereomer. [g] Mixture of diastereomers. [h] Calculated by eq 7.

In order to determine if a *cis*-azo compound isomerizes and/or decomposes, very carefully performed product analyses by capillary gas-phase chromatography were required. For *cis*-A-222 and *cis*-A-321 the activation parameters for both processes were analyzed by temperature-dependent product analyses. For cis-A-ad-nor and cis-A-t no correction for the ≤3% decomposition reaction was introduced.

Thermochemistry. For a comparison and interpretation of the differences in kinetic stability of the various cis and trans isomers of this series, it was of prime importance to have information about the relative thermodynamic stabilities of both isomers, i.e., about the heats of isomerization ΔH_{isom}. They are defined as the differences in heat of formation $\Delta H_f°$(gas) of trans and cis isomers.

$$\Delta H_{isom} = \Delta H_f°(\text{gas, trans}) - \Delta H_f°(\text{gas, cis}) \qquad (2)$$

Heats of formation of *trans*-azo compounds, but not of the thermolabile cis isomers, are available from combustion calorimetry and heats of vaporization.[1,4,32] Heats of isomerization must be obtained, therefore, by direct thermochemical measurements in a DSC calorimeter[18,26] in a nonpolar solvent, in order to come as close as possible to the situation in the gas phase.

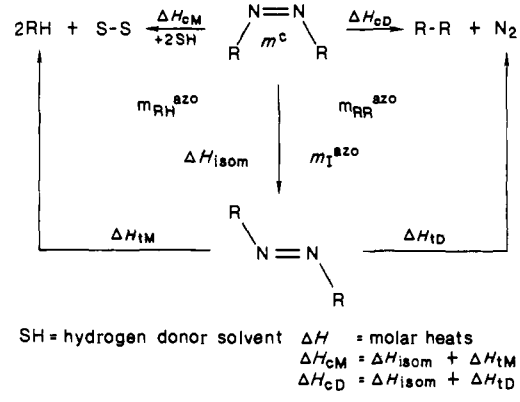
In the same way as for A-211[18] and A-221,[26] the heats of cis–trans isomerization for A-nad and A-bo-221 could be obtained by experiment without correction for homolytic decomposition, because it is at most a negligible competing process in these examples (see Table II). In the other examples of Table II a correction of the thermochemical results for the homolytic decomposition process had to be made.

As the decomposition of the *cis*-azoalkanes (*cis*-RNNR) yielding the hydrocarbons RH and RR is a very exothermic side reaction, one has to correct for it if less than 99.5% of the *cis*-azo compound isomerizes. Since extensive product analyses did not reveal any products other than *trans*-RNNR, RH, RR, and solvent dimers, an exact evaluation of ΔH_{isom} could be made on the basis of a thermochemical cycle (Scheme IV).

For the analysis it is presumed that the cis isomer isomerizes quantitatively to the *trans*-azo compound and that the products RH and RR arise from decomposition of the trans isomer. Therefore the experimentally measured heat of the overall reaction (q_{exp}) has to be corrected for the heat of decomposition of *trans*-RNNR into RR and RH (q_{tD}, q_{tM}; eq 3, with m^c being the amount of reactant and M_r the molecular weight).

$$\Delta H_{isom} = \frac{q_{exp} - q_{tM} - q_{tD}}{m^c/M_r} \qquad (3)$$

Scheme IV



Knowing the amount of RH and RR and consequently the amount of *cis*-RNNR that decomposed into RH (m_{RH}^{azo}) and RR (m_{RR}^{azo}), respectively, we are able to calculate q_{tM} and q_{tD} by using the molar heats ΔH_{tM} and ΔH_{tD}. The molar heats of reaction ΔH_{tM} and ΔH_{tD} have been calculated by using the MMI-derived heats of formation of the reactants and the products.

$$q_{tM} = \frac{m_{RH}^{azo}\Delta H_{tM}}{M_r} \qquad (4)$$

$$q_{tD} = \frac{m_{RR}^{azo}\Delta H_{tD}}{M_r} \qquad (5)$$

As $m^c = m_I^{azo} + m_{RH}^{azo} + m_{RR}^{azo}$, the heat of isomerization can be calculated by eq 6.

$$\Delta H_{isom} = \frac{M_r q_{exp} - m_{RH}^{azo}\Delta H_{tM} - m_{RR}^{azo}\Delta H_{tD}}{m^c} \qquad (6)$$

The accuracy of the quantitative product determinations is, of course, the most critical part of this analysis. The main products, the *trans*-diazenes, were determined by isothermal GC. Internal standards were added before performing the DSC measurements. The GC factors correlating concentrations with peak areas were determined independently under identical conditions as used in the analysis. Standard deviations in yields from 0.5% to 2.0% were obtained. The yields of RR and RH (which are formed only in very small amounts) were determined from independent and temperature-programmed GC measurements with the *trans*-azoalkanes serving as internal standards. The GC factors for the hydrocarbons RR and RH were obtained by the well-established increment procedure.[2,33]

Because the purity of the thermolabile cis isomers could not be determined with the required accuracy, each isomerization was measured in several completely independent experiments. The

(29) Kratt, G.; Beckhaus, H.-D.; Rüchardt, C. *Chem. Ber.* **1984**, *117*, 1748.
(30) Fogel, L. D.; Rennert, A. M.; Steel, C. *J. Chem. Soc., Chem. Commun.* **1975**, 536.
(31) Schulz, A.; Rüchardt, C. *Tetrahedron Lett.* **1976**, 3883.
(32) Engel, P. S.; Wood, J. L.; Sweet, J. A.; Margrave, J. L. *J. Am. Chem. Soc.* **1974**, *96*, 2381. Engel, P. S.; Montgomery, R. L.; Månsson, M.; Leckonby, R. A.; Foyt, H. L.; Rossini, F. D. *J. Chem. Thermodyn.* **1987**, *10*, 205. Montgomery, R. L.; Engel, P. S.; Leckonby, R. A.; Rossini, F. D.; Månsson, M.; Szilagyi, S.; Timberlake, J. W. *J. Chem. Eng. Data* **1978**, *23*, 129.
(33) Kaiser, R. *Chromatographie in der Gasphase*, 2nd ed.; Bibliographisches Institut: Mannheim, **1969**; Vol. 2, p 255.

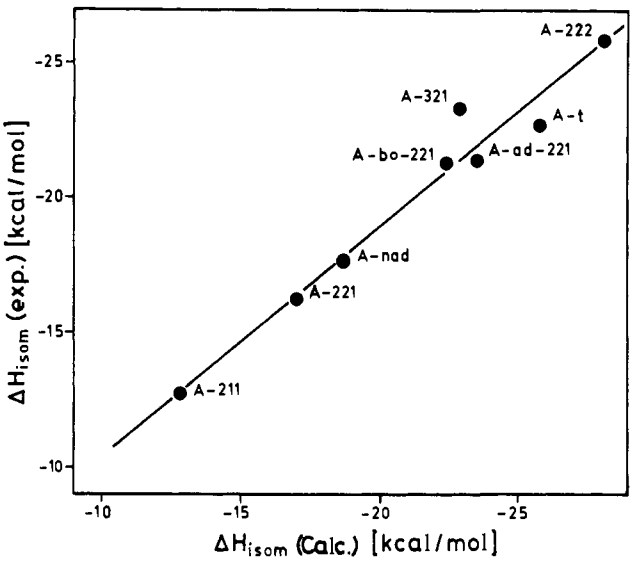


Figure 1. Correlation of experimental and calculated[21b] heats of cis–trans isomerization of azo compounds.

fact that highly reproducible results were obtained, when recrystallized fractions from different preparations of the cis isomers were used, proved that they were sufficiently pure.

The heats of isomerization and the number n of experiments performed for calculating their mean values are reported in Table II. They were used to test the ΔH_{isom} values calculated by the force field method as the difference between the heats of formation of the trans and cis isomers. The agreement with the values obtained by the Snyder force field[21b] was distinctly better than the agreement with those of the Kao force field,[21a] which gave heats of formation of the cis compounds up to 6 kcal·mol^{-1} too small. The calculated values are recorded together with the experimental ones in Table III. The plot in Figure 1 demonstrates the excellent linear relationship between the experimental and calculated heats of isomerization, which follows the correlation equation[34] (eq 7).

$$\Delta H_{isom}(exp) = 0.862\Delta H_{isom}(calcd) - 1.64 \text{ kcal·mol}^{-1} \quad (7)$$
$$(r = 0.982)$$

This equation allows the reliable estimation of heats of isomerization for those *cis*-azo compounds, which cannot be measured experimentally because of the competing or dominating homolytic decomposition. The two values so estimated for A-ad and A-*t*-but are therefore recorded in the column of experimental results in Table III.

Discussion

The kinetic and thermochemical data in Tables I and II, combined with results from the literature,[4,10,16,18,22,26] now permit a closer analysis of the enthalpy diagrams for the thermal reactions of this series of *cis*- and *trans*-diazenes. In order to make a comparison possible, a common reference point for the enthalpy scales had to be chosen. We have decided to define for this purpose the enthalpies of the *trans*-diazenes as zero points in all diagrams, because they are free of strain[35,36] as pointed out later and because experimental data are available for some of them. Additionally, they are well reproduced by force field calculations.[26]

In Table IV the strain enthalpies H_s[35,36] of four *trans*-diazenes are compared with those of the corresponding monomeric hydrocarbons RH. Each azo compound has, within the error limits, twice the strain enthalpy of the hydrocarbon Rh. The ring strain of the polycyclic hydrocarbon units is, therefore, exclusively responsible for the strain of these *trans*-diazenes, and no additional strain is caused by interaction of these groups in the trans isomers.

Next, the heats of isomerization of *cis*-diazenes to the trans isomers, ΔH_{isom}(cis–trans), will be considered. The correlation of experimental heats of isomerization with force field results, shown in Figure 1, adds confidence to the force field method and makes enthalpies of all *trans*- and *cis*-diazenes of this series of azo compounds available (eq 7). Their values are recorded in Table III. The heats of isomerization obtained from these data increase roughly in parallel with the size of the polycyclic alkyl groups of the azoalkanes. This steric effect must be discussed on the basis of strain in the cis isomer since no specific strain in the trans isomer had been found. However, the shape of these substituent groups has some influence too, as demonstrated by the 3 kcal·mol^{-1} smaller heat of isomerization of (*R*,*R*)-A-t than of A-222 (cf. Table III).

Engel had reported previously a linar relationship between the heats of cis–trans isomerization of three *cis*-diazenes and their λ_{max} values.[18,37] As seen from Figure 2, this relationship is confirmed by our newly available data. Structure information provides additional insight for the interpretation of these results. Fortunately, structure data are available from the force field calculations, which have been tested previously and successfully for structure data of azo compounds.[21b,26] Typical results for a series of azo compounds are recorded in Table V together with their UV spectra.

For *trans*-azoalkanes the uniform and normal bond angles as well as torsion angles around the azo group indicate little change of their regular structures within the series as expected. In the cis series, however, the polycyclic ring systems have to get out of each others way, in order to escape serious van der Waals interactions. Therefore, with growing bulk the NNC bond angles are widened to 122–129°. In addition, steric crowding leads one $NC_\alpha C_\beta$ angle to increase (e.g., in azoadamantane to 123.1°).[2] The deviations from the ideal cis geometry are remarkably small even in highly strained *cis*-azo compounds[26] as seen from the small

Table IV. Strain Enthalpies of Some Bridgehead *trans*-Azo Compounds RN_2R and Related Hydrocarbons RH (EFF Results[21b])[b]

R	*trans*-RNNR H_s, kcal/mol	RH H_s, kcal/mol
1-bicyclo[2.1.1]hexyl	84.1 (A-211)	43.1
1-bicyclo[2.2.1]heptyl	32.5 (A-221)	16.7
1-twistyl	41.0[a] (A-t)	21.0
1-bicyclo[2.2.2]octyl	20.8 (A-222)	11.0

[a] (*R*,*R*) diastereomer. [b] See text for EFF results.

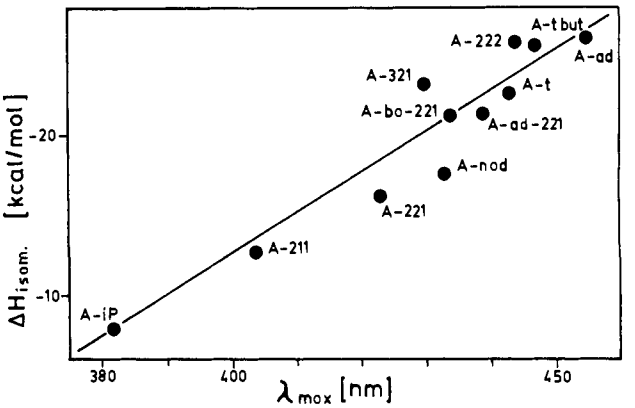


Figure 2. Relationship between ΔH_{isom}(cis–trans) and λ_{max} of azo compounds.

(34) The deviation of A-321 from the correlation in Figure 1 is probably due to a still unsatisfactory eff result in this case.

(35) The strain enthalpies used are defined according to P. v. R. Schleyer's formalism[36] $H_s = \Delta H_f° - \Delta H_f^N$. Because no "single conformation increments"[36] for *trans*-azoalkanes had been derived previously,[21] we defined *trans*-A-*t*-but as the strain-free reference substance ($\Delta H_f°$(exp) = 8.51 kcal·mol^{-1})[10b] and obtained the strain-free group increment[21b] $\Delta H_f^N(C_q\text{–N=N–}C_q)$ = 51.79 kcal·mol^{-1}.

(36) Schleyer, P. v. R.; Williams, J. E.; Blanchard, K. R. *J. Am. Chem. Soc.* **1970**, *92*, 2377.

(37) (a) Ackermann, M. N.; Graig, N. C.; Isberg, R. R.; Lauter, D. M.; Mc Phail, R. A.; Young, W. G. *J. Am. Chem. Soc.* **1977**, *99*, 1661. (b) Dürr, H.; Ruge, B. *Top. Curr. Chem.* **1966**, *66*, 53.

Table V. NNC Bond Angles, CNNC Torsion Angles, Molecular Symmetries (from Force Field Calculations[21b]), and UV Spectra of Bridgehead Azo Compounds[a]

	trans isomer			cis isomer			$\lambda_{max}(\epsilon)$,[d] nm	
azo compd[b]	∠NNC	∠CNNC	point group	∠NNC	∠CNNC	point group	trans	cis
A-211	111.4	180.0	C_i	122.5	0.5	C_1	370 (21)[18]	404 (118)[18]
A-221	111.0	179.9	C_i	125.6	0.1	C_2	369 (15)[26]	423 (88)[26]
A-nad	111.9	180.0	C_i	126.4	0.5	C_2	368 (17)	433 (103)
A-222	112.5	180.0	C_i	129.8	0.4	C_2/C_1[c]	369 (15)	444 (86)
A-ad	111.7	180.0	C_i	129.8	0.3	C_2	370 (14)	455 (93)[18]
A-*t*-but	112.5	179.9	C_i	128.6	0.6	C_1[c]/C_1[c]	366 (13)[37a]	447 (100)[4]
A-t (*R*,*R*)	112.4	179.7	C_1	128.6	0.4	C_2	369 (18)	443 (83)
A-t (*R*,*S*)	112.3	180.0	C_i	127.8	0.1	C_1		
				129.1				
A-321 (*R*,*R*)	112.3	179.3	C_1	128.0	0.7	C_1[c]	367 (15)	430 (103)
A-321 (*R*,*S*)	112.1	179.8	C_i	126.8	0.1	C_i		
				128.0				
A-ad-221	111.7	179.2	C_1	127.4	0.8	C_1	366 (14)	439 (106)
	112.4			127.9				
A-bo-221	111.5	179.6	C_1	127.3	0.7	C_1	373 (14)	434 (105)
	112.4			127.5				

[a] Units of angles in degree. [b] See Chart I. [c] Very close to C_2 symmetry. [d] Azomethane:[37a] trans, 352 (25); cis, 368 (240). 1-Methylazoethane: trans, 357 (17);[37b] cis, 382 (140).[4]

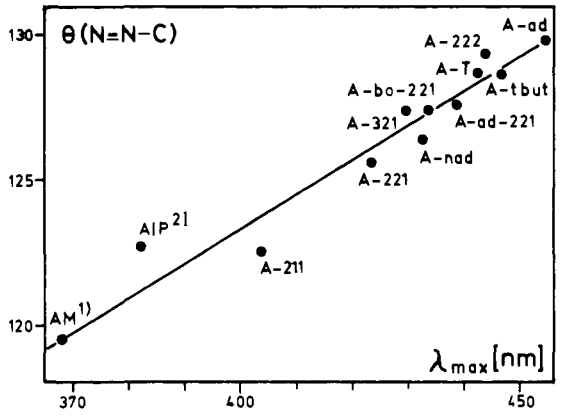


Figure 3. Correlation of the NNC bond angles vs. λ_{max} of *cis*-azoalkanes. (Data from Table V and from force field calculations for azomethane and 1-methylazoethane, A-*i*-P.)[21b]

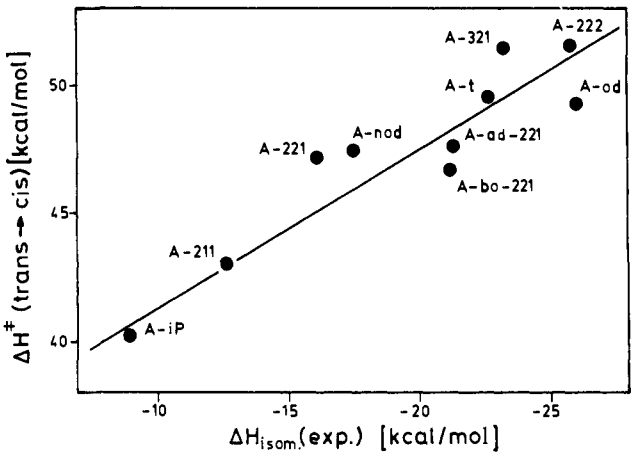


Figure 4. Bell–Evans–Polanyi relationship between enthalpies of activation, $\Delta H^{\ddagger}$, and heats of reaction, ΔH_{isom}, for trans–cis isomerizations of azo compounds.

CNNC torsional angles in Table V. For the dipole moments of the *cis*-azo compounds, 3–4 D (gas phase, DK = 1[38a]) are calculated.[21]

The UV spectra of the *trans*-azoalkanes show the typical weak absorption (ϵ 12–25)[37,38b,c] for the forbidden n–π^* transition between 350 and 380 nm (Table V). The *cis*-azo compounds absorb at longer wavelengths (368–455 nm) with 10 times higher extinction coefficients (Table V). A surprisingly good linear relationship is observed between λ_{max} and the NNC bond angles of the *cis*-azoalkanes, as shown in Figure 3.[39,40]

The deviations of A-321, A-222, and A-*t*-but from the correlation of heats of isomerization vs. λ_{max} in Figure 2 can now be discussed on a structural basis. These azo compounds are the ones with the most flexible R groups within the series.[41] However, λ_{max} represents only that fraction of the total strain of a *cis*-diazene which is leading to an increase of the NNC bond angle (Figure 3). Deformation of a flexible R group apparently has no effect on λ_{max} but certainly on ΔH_{isom}, because it will be released in the process of cis–trans isomerization. The low negative heats of isomerization of *cis*-A-221 and A-nad, as judged from Figure 2, in contrast, may be due to the deficiency in flexibility of their R groups.

The heat of cis–trans isomerization of A-*t*-but (Table III) is large if compared with the ΔH_{isom} of *cis*-1,2-di-*tert*-butylethylene (11 kcal·mol^{-1})[42] or with the strain enthalpy of *o*-di-*tert*-butylbenzene (22 kcal·mol^{-1}).[43] The increase in the NNC bond angle in *cis*-azoalkanes, e.g., in *cis*-A-221 (129.3°)[26] (see also Table V), is also large. The shorter distance of N=N bonds (124–126 pm)[26] than of C=C bonds (135–140 pm) explains both phemomena.

What can be said about the transition state of the cis–trans isomerization from our new data? The postulate[18] of isoenergetic transition states for the trans–cis isomerization process is not confirmed. To make this clear, the enthalpies of activation of the trans–cis isomerization, $\Delta H^{\ddagger}$(trans–cis), have been calculated by using the activation enthalpies for the cis–trans isomerization, $\Delta H^{\ddagger}$(cis–trans) (Table II), and the enthalpies of the cis–trans isomerization, ΔH_{isom}(cis–trans):

$$\Delta H^{\ddagger}(\text{trans–cis}) = \Delta H^{\ddagger}(\text{cis–trans}) - \Delta H_{isom}(\text{cis–trans}) \quad (8)$$

Their values range between 42 kcal·mol^{-1} for A-211 and 52 kcal·mol^{-1} for A-222 (see Table III). From the enthalpies of activation for the hypothetical trans–cis isomerization, further interesting conclusions can be drawn. In a Bell–Evans–Polanyi

(38) (a) Allinger, N. L., QCPE Program description No. 318 for MM1, Indiana University, 1975. (b) Robin, M. B. In *The Chemistry of the Hydrazo, Azo and Azoxy Groups*; Patai, S., Ed.; Wiley-Interscience: New York, 1975; p 1. (c) Allmann, R. *Ibid.* p 23.

(39) It has been shown by ab inito calculations for cyclic *cis*-azo compounds that the energy of the n-MO is increased with increasing NNC bond angle, due to the closer proximity of the free electron pairs.[40] The situation in open-chain *cis*-azo compounds apparently is very similar (see Figure 3).

(40) Baier, N. C.; de Mayo, P.; Swenson, J. R.; Usselmann, M. C. *J. Chem. Soc., Chem. Commun.* **1973**, 314.

(41) Perlmutter, H. D.; Kristal, D. S.; Tomkins, R. P. T. *J. Am. Chem. Soc.* **1984**, *106*, 340 and ref 18 of this paper.

(42) Allinger, N. L.; Sprague, J. T. *J. Am. Chem. Soc.* **1972**, *94*, 5734.

(43) Arnett, E. M.; Sander, J. C.; Ballinger, J. M.; Barbe, M. *J. Am. Chem. Soc.* **1967**, *89*, 5389.

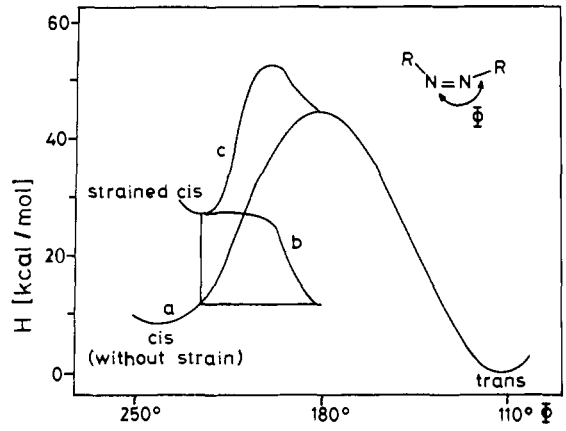
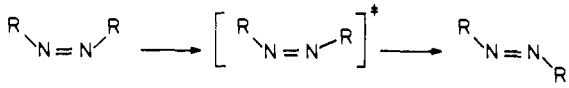


Figure 5. Reaction coordinate c for the cis–trans isomerization of strained azo compounds (see text).

Scheme V



plot[44] they are linearly related to the heats of isomerization (see Figure 4). This is good evidence for a common mechanism of isomerization within the whole series. The $\Delta H^{\ddagger}$(trans–cis) values in Table III compare favorably with values obtained by MO calculations for the inversion mechanism of diimine and azomethane (37–66 kcal·mol^{-1}).[45]

The order of these activation enthalpies, $\Delta H^{\ddagger}_{isom}$(trans–cis), also allows some conclusions about the transition state. The fact that $\Delta H^{\ddagger}_{isom}$(trans–cis) decreases in the series A-222 > A-221 > A-211 (i.e., with decreasing stability of their resulting radicals, R$^{\bullet}$) contradicts the alkyl diazenyl radical pair mechanism suggested recently.[11a,b,12a,b] All experimental facts presented so far accordingly point to the previously discussed[4,11c,26] inversion mechanism for the cis–trans isomerization. Further support comes from the $\Delta H^{\ddagger}$(trans–cis) values for the two unsymmetrical azo compounds A-ad-221 and A-bo-221 in Table III. They correspond within the experimental error to $\Delta H^{\ddagger}$(trans–cis) for A-221, which is strong evidence against the diazenyl radical pair mechanism. As both unsymmetrical systems have the 1-bicyclo[2.2.1]heptyl group on one side, the inversion of this group is probably the mechanism for all three compounds. This could be the least motion process in the unsymmetrical systems. This is in agreement with the observed low activation entropies $\Delta S^{\ddagger}$(cis–trans).

Finally, a few remarks are appropriate concerning the geometry of the transition state of the inversion mechanism. The frequently postulated semilinear geometry[4,18,26] is probably only the extreme situation for a transition state leading to a *hypothetical* strainless *cis*-azo compound. The following discussion will come to the conclusion that the transition state generally is in between the cis configuration and the semilinear state (Scheme V).

Force field calculations have shown (see above) that the strain enthalpies H_s of the trans isomers of the series are only due to the strain of the polycyclic ring systems and not to any interaction between them. According to calculations fixing the groups in a semilinear arrangement (one NNC angle = 180°), no interaction between the R groups is recognized. On the other hand, the activation enthalpies $\Delta H^{\ddagger}$(trans–cis) increase with increasing heat of isomerization. At the transition state, part of the strain of the cis isomers must already be in action. According to the Hammond postulate the transition-state geometry must, therefore, resemble

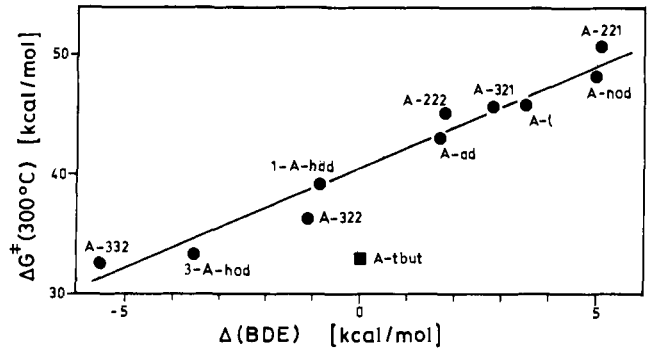
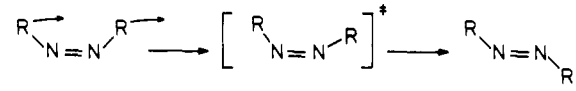


Figure 6. Correlation of $\Delta G^{\ddagger}$(300 °C) for the decomposition of trans bridgehead azo compounds from Table I and bridgehead C–H bond dissociation enthalpies.[49] The tertiary C–H bond in isobutane is the reference point.[49b]

Scheme VI



the cis isomer. This is especially true for those azo compounds which have the highest $\Delta H^{\ddagger}$(trans–cis), i.e., the most bulky ones. A model reaction coordinate to explain this is shown in Figure 5.

In Figure 5, curve a describes the change in potential energy of an unstrained azo model compound with changing angle ϕ, with the minimum of the curve being around 240° in the cis and 110–120° in the trans isomer. This graph represents the change in electronic energy, i.e, mainly the electron repulsion term. A strained *cis*-azo compound has a higher potential due to steric repulsion between the R groups. This repulsion results in increased NNC bond angles (see above), or a decrease in ϕ to about 220°. If one assumes that the change in strain with decreasing angle ϕ follows curve b, then, by addition of a and b, curve c results for the reaction coordinate, and a transition-state geometry with 220° > ϕ > 180° follows. It is assumed that the steric potential represented by curve b does not decrease immediately with a reduction in ϕ. When one R group starts moving toward semilinearization, the other R group probably responds to this movement until it has reached its regular NNC bond angle of about 115° (Scheme VI).

Another point not yet discussed is the competition between isomerization and homolytic decomposition for *cis*-azo compounds. For small polycyclic examples which must decompose into bridgehead radicals of high energy, the enthalpy of activation for the cis–trans isomerization is smaller than for the decomposition. With decreasing ring strain of the radicals being generated, and with increasing bulk, the homolytic decomposition becomes favored over isomerization. For *cis*-A-ad, A-222, and A-321 the activation enthalpies for the homolytic decomposition are known (Table II).

The high activation entropies for the decomposition of cis isomers (Table II) may be due to interlocking interaction between the R groups in the cis isomers, which are released at the transition state.

The new data in Table I also throw a new light upon the mechanism of thermal decomposition of the bridgehead *trans*-diazenes. The observation of an isokinetic relationship (see above) is good evidence for a homogeneous mechanism of thermolysis within the whole series. This contrasts with our former conclusion[16] of a change in mechanism, which was based on a break in the correlation between log k of azo homolyses and log k of the solvolysis of bridgehead bromides.

An even better test would be a Bell–Evans–Polanyi plot[44] between the activation enthalpies and the corresponding C–H bond energies of bridgehead hydrogens, as it exists for the decomposition of simple azoalkanes.[3,46] Since the kinetics within the series of

(44) Wentrup, C. *Reaktive Zwischenstufen*; Georg Thieme Verlag: Stuttgart, 1979; Vol. I, p 4.

(45) Baird, N. C.; Swenson, J. R. *Can. J. Chem.* **1973**, *51*, 3097. Camp, R. N.; Epstein, I. R.; Steel, C. *J. Am. Chem. Soc.* **1977**, *99*, 2453. Kearns, D. R. *J. Phys. Chem.* **1965**, *69*, 1062. Howell, J. M.; Kirschenbaum, J. L. *J. Am. Chem. Soc.* **1976**, *98*, 877. Gordon, M. S.; Fischer, H. *J. Am. Chem. Soc.* **1968**, *90*, 2471. Winter, M. W.; Pitzer, R. M. *J. Chem. Phys.* **1975**, *62*, 1269. Olbrich, G. *Chem. Phys.* **1978**, *27*, 117.

(46) Takagi, K.; Crawford, R. J. *Can. J. Chem.* **1970**, *48*, 2745.

Table VI. $\Delta G^{\ddagger}$(300 °C) Values for Symmetrical and Unsymmetrical *trans*-Azo Compounds[16] (kcal/mol)

compd	R^1	R^2	$\Delta\Delta G^{\ddagger}(1)^a$	$\Delta\Delta G^{\ddagger}(2)^b$
A-*t*-but-nor	1-norbornyl	*tert*-butyl	−10.9	6.4
A-ad-nor	1-norbornyl	1-adamantyl	−4.4	3.2
A-bo-nor	1-norbornyl	1-bicyclo[2.2.2]-octyl	−3.2	2.3

$^a \Delta G^{\ddagger}(R^1N_2R^1) - \Delta G^{\ddagger}(R^1N_2R^2)$. $^b \Delta G^{\ddagger}(R^2N_2R^2) - \Delta G^{\ddagger}(R^1N_2R^2)$.

bridgehead *trans*-diazenes were measured between 170 and 400 °C, correlations of $\Delta G^{\ddagger}$ are preferred over those of $\Delta H^{\ddagger}$. Due to the compensation effect,[47,48] the order of decreasing $\Delta G^{\ddagger}$ values is less dependent on temperature and therefore more significant for structural interpretation. Bridgehead C–H bond energies obtained from force field calculations by Beckhaus, using his force field for radicals,[49] correlate bridgehead azo decompositions well as seen from the plot of the data from Table I and Figure 6.

The slope $m = 1.8$ of this correlation is remarkable as it seems to express that the development of both radicals R is already far advanced at transition state. In the frame of the Ramsperger criterion[6] this is evidence for the one-step concerted fragmentation mechanism. The only nonbridgehead tertiary azo compound of Table I, A-*t*-but does not follow the correlation in Figure 6 well.

A correlation of the free energies of activation $\Delta G^{\ddagger}$(300 °C) from Table I vs. the unified data set for bridgehead solvolysis reactivity provided by Bentley[50] again is curved and not linear, similar to the plot which we have provided in 1977.[16]

In addition to the enthalpy discussion of the rate data in Table I, comments on the changes in entropy of activation are required. The fact that $\Delta S^{\ddagger}$ increases with the flexibility of the polycyclic ring system, and most signifanctly for the only open-chain compound within this series (A-*t*-but), allows the conclusion that by the geometric changes during the activation process degrees of freedom for rotational and vibrational movement are set free, which are hindered in the ground-state azo compounds. Similarly, the difference in thermal stability of 2,2,3,3-tetramethylbutane and 1,1′-bis(adamantane) was found to be much more due to the difference in $\Delta S^{\ddagger}$[51] than to a difference in enthalpic stability of *ter*-butyl and 1-adamantyl radicals.[49b] The small activation entropy for the generation of the very rigid 1-norbornyl radical from A-221 ($\Delta S^{\ddagger}$ = 3.2 eu) allows the conclusion that the entropy effects are mainly due to changes in the internal degrees of freedom of rotation and not to an increase in the number of particles. For entropic as well as for enthalpic reasons (see below) it must be concluded, therefore, that the two R groups and the N_2 molecule are still loosely bound to each other at the transition state. Using the program DELFI,[52] Beckhaus was able to calculate the differences in standard entropy $\Delta S^{\ddagger}$ between bridgehead hydrocarbons RH and radicals R·.[49] The good linear correlation between $\Delta S^{\ddagger}$ from Table I and these ΔS values[49] stresses this point.[2]

Additional evidence for a concerted pathway of the decomposition of trans bridgehead azo compounds comes from the rates of the three unsymmetrical azo compounds in Table I. As seen in Table VI, their free enthalpies of activation $\Delta G^{\ddagger}$(300 °C) fall right in the middle between the $\Delta G^{\ddagger}$(300 °C) values of the corresponding pairs of symmetrical azo compounds. Following the Ramsperger criterion[3,6,7] this is strong evidence for the concerted two-bond fragmentation mechanism.

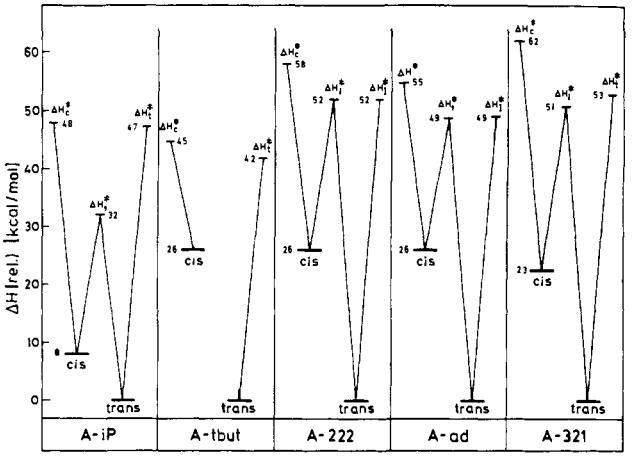


Figure 7. Enthalpy diagrams for selected *cis*- and *trans*-azo compounds and their homolytic decomposition.

Scheme VII

The thermochemical and kinetic data reported in this work are integrated for a few representative azo compounds for comparison in the reaction coordinates in Figure 7.

For *cis*-A-ad, *cis*-A-222, and *cis*-A-321, the enthalpy levels of the activated states for decomposition, $\Delta H^{\ddagger}_c$, are higher than for the corresponding *trans*-diazenes ($\Delta H^{\ddagger}_t$).

This is in contrast to Dannenberg's calculations, which came to the conclusion that *trans*-azoethane decomposes via the cis isomer. Although our interpretations are somewhat tentative (since the activation enthalpies for *cis*- and *trans*-azo compounds are determined at very different temperatures), the postulate that *cis*- and *trans*-azo compounds decompose via one and the same transition state is no longer convincingly supported. Due to the highly positive $\Delta S^{\ddagger}_c$, which at higher temperature favors decomposition of the *cis*-azo compounds over cis–trans isomerization, one might argue that *trans*-azo decomposition is actually proceeding via trans–cis isomerization followed by *cis*-azo decomposition. However assuming a plausible $\Delta S^{\ddagger}_c$ of −5 eu,[55] the calculated activation energies disfavor trans–cis isomerization (e.g., A-222: $\Delta G^{\ddagger}_{tc}$(300 °C) = 54.5 kcal·mol^{-1}) compared to trans decomposition (A-222: $\Delta G^{\ddagger}_t$(300 °C) = 45.5 kcal·mol^{-1}). The assumption of different transition-state geometries for the concerted fragmentations is an attractive hypothesis for the difference in the $\Delta H^{\ddagger}$(dec) enthalpy level (Figure 7) of *cis*- and *trans*-diazenes (Scheme VII).

For A-*i*-P and A-*t*-but on the other hand, the enthalpy levels of the transition states for decomposition of the cis and trans isomers are very similar (see Figure 7). Interestingly, for these compounds the activation entropies for the decomposition of the cis and the trans isomers are almost the same.

Experimental Section

All manipulations, either to purify or to manipulate *cis*-azo compounds, were carried out simultaneously under red light and at low temperatures to avoid unintended cis–trans isomerization. Proton NMR spectra were recorded on a Bruker WM-250, carbon NMR spectra on a Bruker WP-80. The UV analyses were carried out either on a Zeiss DMR 21 or on a Zeiss PMQ III spectrophotometer.

Synthesis of *trans*-Diazenes. The *trans*-diazenes were prepared as previously described[16] from the corresponding sulfamides and ureas.

trans-1-Azobicyclo[2.2.1]heptane was obtained in 46% yield after purification by chromatography (basic alumina, *n*-hexane) and recrystallization (methanol): mp 162 °C [lit.[16] mp 166–167 °C]; ^{1}H NMR (CCl_4) δ 1.28–1.93 (m, 20 H), 2.27 (m, 2 H); ^{13}C NMR ($CDCl_3$) δ 30.07

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(55) $\Delta S^{\ddagger}_{1c}$ has been arbitarily chosen: according to our reaction coordinate the transition state of trans–cis isomerization invokes a lot of strain that should result in the loss of rotational and vibrational degrees of freedom.

(t), 32.28 (t), 36.64 (d), 42.01 (t), 82.62 (s).

trans-1-Azobicyclo[2.2.2]octane was obtained in 86% yield after chromatography (basic alumina, *n*-hexane) and recrystallization (methanol): mp 133 °C [lit.[16] 133–134 °C]; ^{1}H NMR (CCl_4) δ 1.83 (br d, 24 H), 1.83 (mc, 2 H); ^{13}C NMR ($CDCl_3$) δ 25.74 (d), 26.36 (t), 29.50 (t), 66.64 (s).

trans-1-Azotwistane was prepared in 98% yield (crude) from the corresponding sulfamide, purified by chromatography (basic alumina, *n*-hexane), and recrystallized from methanol: mp 131.5–132 °C [lit.[16] mp 125–127 °C]; ^{13}C NMR ($CDCl_3$) δ 22.08 (t), 24.08 (t), 25.55 (t), 29.06 (t), 29.13 (t), 29.3 (d), 32.73 (t), 32.84 (d), 70.48 (s).

trans-1-Azobicyclo[3.2.1]octane was obtained in 89% yield after chromatography (basic alumina, *n*-pentane) and recrystallization (methanol): mp 132.5–133 °C [lit.[16] mp 134.0–135.5 °C]; ^{1}H NMR ($CDCl_3$) δ 1.30–1.90 (m, 24 H), 2.32 (mc, 2 H); ^{13}C NMR ($CDCl_3$) δ 19.77 (t), 28.26 (t), 32.03 (t), 32.17 (t), 35.23 (d), 35.61 (t), 42.46 (t), 77.95 (s).

trans-3-Azonoradamantane[16] was prepared in 66% yield (crude) and was purified by chromatography (basic alumina, petrol ether) and recrystallization (methanol): mp 202–204 °C; ^{1}H NMR ($CDCl_3$) δ 1.52–1.74 (m, 12 H), 1.90 (mc, 4 H), 2.02 (m, 4 H), 2.34 (mc, 4 H), 2.50 (m, 2 H); ^{13}C NMR ($CDCl_3$) δ 35.44 (t), 37.68 (d), 42.43 (d), 43.87 (t), 47.28 (t), 83.48 (s).

trans-1-Azoadamantane was obtained in 85% yield and purified by chromatography (basic alumina, petrol ether) and recrystallization (methanol): mp 280–284 °C [lit.[16] mp 280–285 °C]; ^{1}H NMR ($CDCl_3$) δ 1.71 (mc, 24 H), 2.13 (br s, 6 H); ^{13}C NMR ($CDCl_3$) δ 29.47 (d), 36.78 (t), 40.46 (t), 66.47 (s).

trans-*N*-(1-Bicyclo[2.2.1]heptyl)-*N*′-(1-bicyclo[2.2.2]octyl)diazene was provided by F. Groeger:[16] ^{13}C NMR ($CDCl_3$) δ 25.71 (d), 26.35 (t), 29.55 (t), 30.07 (t), 32.24 (t), 36.04 (d), 41.94 (t), 66.86 (s), 82.50 (s).

trans-*N*-(1-Bicyclo[2.2.1]heptyl)-*N*′-(1-adamantyl)diazene was prepared from the unsymmetrical urea and purified by chromatography (basic alumina, toluene) and recrystallization from methanol/water (95/5): mp 170–172 °C [lit.[16] mp 170–171 °C]; ^{1}H NMR ($CDCl_3$) δ 1.26 (br s, 1 H), 1.47 (mc, 3 H), 1.57–1.83 (m, 18 H), 2.14 (br s, 3 H), 2.32 (br s, 1 H); ^{13}C NMR ($CDCl_3$) δ 29.48 (d), 30.12 (t), 32.31 (t), 36.09 (d), 36.79 (t), 40.46 (t), 41.99 (t), 66.87 (s), 82.37 (s).

Synthesis of *cis*-Diazenes. General Experimental Procedure. An approximately 0.035 M solution of the *trans*-azoalkane in pentane or toluene, respectively, was irradiated at 350 nm (Rayonet reactor) at a temperature which was suitably low to prevent thermal cis–trans isomerization. The photostationary state is essentially reached after 30 min. This is indicated by the intense yellow color of the solution, corresponding to the presence of cis isomer. The resulting cis–trans mixture was separated by using a 1.5- × 10-cm basic alumina column at the same temperature employed for the irradiation. The cis isomer remained fixed at top while the *trans*-azo compound was eluted without any retention. The eluted *trans*-azoalkane was resubmitted to irradiation and chromatographed once again on the same column. This allowed the cis isomer to accumulate on the column with each new cycle.

To purify the fixed *cis*-azoalkane, the column was washed twice with 30 mL of toluene, followed by 60 mL of pentane. Finally the pure cis isomer could be eluted with 30 mL of methanol. After addition of a few milligrams of sodium bicarbonate the solvent was stripped off in vacuo by rotary evaporation. Yields have not been determined. The *cis*-azoalkanes—with the exception of *cis*-azoadamantane—could be stored at −70 °C without significant decomposition. Prior to kinetic and thermodynamic experiments they were recrystallized from a nonpolar solvent to remove any trace of trans material.

cis-1-Azobicyclo[2.2.1]heptane was obtained after irradiation in petroleum ether and chromatographed on basic alumina at 15 °C eluting with petroleum ether. The cis product was recrystallized from petroleum ether at −30 °C: mp 94–97 °C [lit.[26] mp 92–93 °C]; ^{1}H NMR ($CDCl_3$) δ 1.36–1.93 (m, 14 H), 2.14 (m, 6 H), 2.24 (mc, 2 H); ^{13}C NMR ($CDCl_3$) δ 30.77 (t), 32.28 (t), 34.33 (d), 47.76 (t), 81.45 (s); UV (isooctane) λ_{max} 423 nm (ϵ 88).

cis-1-Azobicyclo[2.2.2]octane was obtained after irradiation in pentane and chromatography with pentane at −25 °C. The pure sample was recovered by recrystallization from *n*-pentane at −30 °C: ^{1}H NMR ($CDCl_3$) δ 1.63 (mc, 14 H), 2.01 (mc, 12 H); ^{13}C NMR ($CDCl_3$) δ 23.87 (d), 26.30 (t), 31.10 (t), 69.81 (s); UV (toluene) λ_{max} 444 nm (ϵ 86).

cis-1-Azotwistane was obtained after irradiation of the trans isomer in pentane and chromatography at −15 °C. Recrystallization from hexane at −70 °C afforded a diastereomeric mixture of the cis isomers. This is indicated by two sets of ^{13}C NMR data, which must represent the meso and the D,L diastereomers but cannot be further assigned at this time: ^{1}H NMR ($CDCl_3$) δ 1.34–2.03 (m, 24 H), 2.03 (m, 6 H); ^{13}C NMR ($CDCl_3$) δ 22.76 and 22.81 (t), 23.80 and 23.86 (t), 25.68 and 25.72 (t), 27.98 and 28.03 (d), 28.22 and 28.34 (t), 28.78 and 28.86 (t), 29.35 and 29.42 (d), 35.22 and 35.42 (d), 37.33 and 37.92 (t), 72.30 and 72.68 (s); UV (toluene) λ_{max} (ϵ 73).

cis-1-Azobicyclo[3.2.1]octane was isolated in pure form after irradiation of the trans isomer at −25 °C by column chromatography and recrystallization from pentane at −70 °C. Once again, the two sets of NMR data are believed to represent the different diastereomers: ^{1}H NMR ($CDCl_3$) δ 1.34–2.42 (m, 26 H); ^{13}C NMR ($CDCl_3$) δ 19.78 and 19.88 (t), 28.40 and 28.86 (t), 31.09 and 32.68 (t), 33.68 (t), 34.17 (d), 34.20 and 34.72 (t), 46.57 and 47.63 (t), 79.48 (s); UV (toluene) λ_{max} 430 nm (ϵ 103).

cis-3-Azonoradamantane was obtained after irradiation at −33 °C. The crude sample was recrystallized from pentane at −70 °C: ^{1}H NMR ($CDCl_3$) δ 1.55 (qd, J_1 = 12.7, J_2 = 2.6 Hz, 2 H), 1.62–1.86 (m, 10 H), 2.04 (qd, J_1 = 10.5, J_2 = 2.2 Hz, 8 H), 2.41 (mc, 4 H), 2.52 (tt, J_1 = 7.1, J_2 = 1.8 Hz, 2 H); ^{13}C NMR ($CDCl_3$) δ 35.25 (t), 39.03 (d), 43.09 (t), 47.75 (t), 50.32 (d), 83.96 (s); UV (toluene) λ_{max} 433 nm (ϵ 103).

cis-1-Azoadamantane could be synthesized by irradiation of the trans isomer in toluene at −35 °C. After column chromatography the crude product was obtained by removal of the methanol at −20 °C: ^{1}H NMR ($CDCl_3$) δ 1.73 (br s, 12 H), 2.18 (br s, 12 H), 2.23 (mc, 6 H); UV (toluene) λ_{max} 455 nm.

cis-*N*-(1-Bicyclo[2.2.1]heptyl)-*N*′-(bicyclo[2.2.2]octyl)diazene was prepared at −20 °C in pentane and purified by column chromatography. The yellow powder was recrystallized from pentane at −70 °C: ^{1}H NMR ($CDCl_3$) δ 1.24 (br s, 1 H), 1.50 (mc, 2 H), 1.59–2.02 (m, 18 H), 2.14 (br s, 2 H), 2.29 (mc, 1 H); ^{13}C NMR ($CDCl_3$) δ 23.89 (d), 26.24 (t), 30.12 (t), 33.33 (t), 34.62 (d), 48.12 (t), 68.68 (s), 82.22 (s); UV (toluene) λ_{max} 434 nm (ϵ 105).

cis-*N*-(1-Bicyclo[2.2.1]heptyl)-*N*′-(1-adamantyl)diazene was obtained after irradiation of the corresponding trans isomer in toluene at −25 °C. Chromatography and recrystallization from pentane at −70 °C afforded the pure cis compound: ^{1}H NMR ($CDCl_3$) δ 1.27 (br s, 1 H), 1.50 (mc, 3 H), 1.74–2.20 (m, 21 H), 2.25 (mc, 1 H); ^{13}C NMR ($CDCl_3$) δ 29.79 (d), 30.67 (t), 33.71 (t), 34.74 (d), 36.38 (t), 41.17 (t), 48.90 (t), 50.57 (s), 85.39 (s); UV (toluene) λ_{max} 439 nm (ϵ 106).

Molecular Mechanics Calculations. The calculations were performed on a UNIVAC using Allingers force field MM1[38a] extended with the azoalkane parameter sets of either Snyder[21b] or of Kao[21a] as described previously.[26]

Usually the bicyclic groups were driven through a series of CNNC torsional angles in the search for the lowest minimum. Only the structures with the lowest steric energies are considered in this work.

Kinetics of the *trans*-Azoalkane Thermolysis. The ampule technique was applied for all rate measurements, using a thermostated molten tin bath (±0.1 °C).[53] During thermolysis, the integrity of the azoalkane was monitored by GC. A saturated hydrocarbon was added as an internal standard either before[54] or after[53] the azoalkane thermolysis. Products were identified by comparing their retention times with those of authentic samples and/or by mass spectroscopy.

Kinetics of *cis*-Azoalkane Decomposition. The kinetics were run either by the usual UV technique[26] or more conveniently by the temperature-programmed DSC method.[2,27] The latter allows simultaneous determination of the overall heat of the reaction.

Differential scanning calorimetry was carried out on a Perkin-Elmer DSC-2c using high purity indium and *n*-octadecane as both temperature and heat calibration standards. The DSC-2C was interfaced to a Commodore 8032 which allowed storage and analysis of the data by a dialogue program[2]. All DSC experiments were run by using the same linear temperature program (5 °C/min) over a temperature interval of at least 100 °C in order to get base line resolved peaks. The sensitivity range of the DSC-2c was 0.5 mcal/s.

The *cis*-azo compounds had to be manipulated differently according to their thermal stability. Hence, the more stable *cis*-A-221 and *cis*-A-nad could be weighed into the DSC-pans (1–4 mg) at room temperature and were subsequently dissolved by adding 10 μL of mesitylene. Finally the pans were hermetically sealed.

The thermally less stable *cis*-azo compounds had to be handled at −10 to −30 °C to prevent thermal cis–trans isomerization. Therefore, they were prepared as a saturated solution in an appropriate H-donor solvent (toluene, mesitylene). A 30-μL portion of the solution was transferred via syringe to a 50-μL DSC pan containing a known amount of an inert GC standard. Thereafter the pan was hermetically sealed.

Dissection of the rate constants at constant temperatures for disappearance of *cis*-A-321 and *cis*-A-222 into those for isomerization and decomposition was done by analyzing quantitatively the reaction products (*trans*-RNNR, RH, and RR) by GC.

Determination of the Heats of Isomerization. For an additional description of the procedure refer to the theoretical part. The evaluation of ΔH_{isom} requires knowledge of the exact amounts of both the *cis*-azo compounds and all products (eq 9). Careful product analysis did not

$$\Delta H_{isom} = \frac{\Delta H_{exp}}{m_c} M_r \quad (9)$$

ΔH_{exp}: experimentally determined heat of reaction (mcal)

m_c: amount of *cis*-azoalkane (mg)

reveal any other products other than *trans*-RNNR, RH, RR, and solvent dimers.[56] These were identified by comparing their retention times with those of authentic samples and/or by mass spectroscopy.

As *cis*-A-221 and *cis*-A-nad could be manipulated at room temperature and isomerized quantitatively to the trans isomers, all information was provided by weighing the starting material. For the other *cis*-azo compounds the procedure was more complex; the amounts of all products had to be obtained by two consecutive GC analyses.

The main product, the trans isomer, was determined by an isothermal GC analysis on capillary columns using *n*-hydrocarbons as internal standards. These had been added to the DSC pans prior to the isomerization. By making use of experimental GC factors f, we could determine the absolute amounts m_1 of the trans isomer by the usual procedure.[33] Each sample was analyzed 3–10 times.

$$m_1 = m_{Si} \frac{A_{azo}}{A_{Si}} f \quad (10)$$

m_1: yield of isomerized *trans*-azoalkanes (g)

A: area of the GC peak

m_{Si}: amount of standard (g)

The minor products were determined by a temperature-programmed GC analysis using the formed trans isomer as internal standard. With the GC factors f being available by an increment method[33] (the ones for the *trans*-azoalkanes could be readily reproduced within 2%) it was possible to calculate the relative yields of RH and RR based on *trans*-RNNR (set to 100%). By additionally taking into consideration the stoichiometric equations and the formula weights, the relative ratios of *cis*-azo compound going to *trans*-RNNR, RH, and RR (m_1^{azo}, m_{RH}^{azo}, m_{RR}^{azo}) were calculated.

$$RNNR \xrightarrow{SH} 2RH + N_2 + S\text{-}S \quad (SH: \text{solvent})$$

$$RNNR \rightarrow R\text{-}R + N_2$$

$$m_{RH}^{azo} = \frac{A_{RH}}{A_{azo}} f \frac{M_r(azo)}{2M_r(RH)} \quad (11)$$

$$m_{RR}^{azo} = \frac{A_{RR}}{A_{azo}} f \frac{M_r(azo)}{M_r(RR)} \quad (12)$$

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Regiospecific Synthesis of 2-Methoxy-3-methyl-1,4-benzoquinones from Maleoylcobalt Complexes and Alkynes via Lewis Acid Catalysis. A Highly Convergent Route to Isoquinoline Quinones

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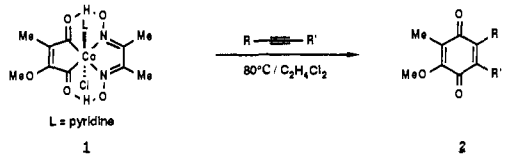
Abstract: Under the influence of Lewis acids such as $SnCl_4$, $BF_3 \cdot Et_2O$, and $AgBF_4$ a maleoylcobalt complex derived from 3-methoxy-4-methylcyclobutenedione reacted with three diverse classes of alkynes (terminal, electron deficient, and propargylsilanes) at room temperature to afford moderate to good isolated yields (40–79%) of substituted benzoquinones with good to excellent regioselectivity in each case (7:1 up to >20:1). Since earlier studies had established excellent regioselectivity for the reaction of electron rich alkynyl ethers with the same maleoylcobalt complex under conditions of *thermal* activation, a wide variety of highly functionalized benzoquinones with substituents commonly encountered in bioactive natural products (2-methoxy-3-methyl-1,4-benzoquinone base) are available by this mild sequence of reactions.

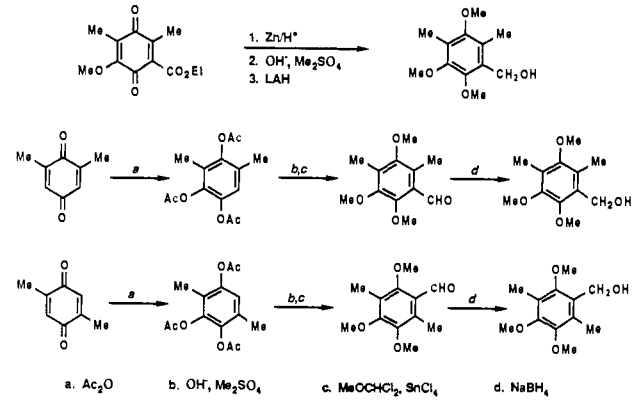
We have previously described the reaction of maleoylcobalt complex **1** with unsymmetrical acetylenes to produce benzoquinones of general structure **2** (eq 1).[2] Under our standard conditions for quinone formation from species such as **1**, reaction



1 2 (1)

at 80 °C in dichloroethane gave high yields of quinones from a wide range of alkynes. The regioselectivity of this thermal reaction varied, with terminal and electron-withdrawing alkynes showing moderate selectivity (ca. 4:1 with **2**, R = alkyl, R′ = H and **2**, R = alkyl, R′ = EWG predominating) while electron rich alkynes

Scheme I



reacted with excellent regioselectivity (13.5:1 with **2**, R = OR, R′ = alkyl predominating). Since quinones of general structure **2** are found in many important antibiotics and anticancer compounds,[3] our ability to predictably control, with good regiose-

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