Dynamics of intramolecular carbenic rearrangements

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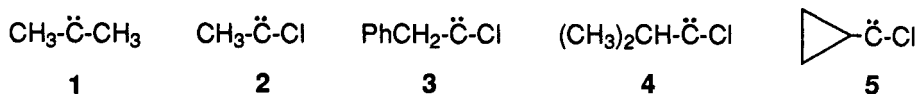
Abstract: This report deals with several topics of current interest in mechanistic carbene chemistry, including the absolute kinetics of carbenic rearrangements; substituent effects on 1,2-shifts; entropic control in carbenic rearrangements; the involvement of electronically excited diazirines as carbene mimics; and the magnitude of kinetic isotope effects, particularly in 1,2-H(D) migrations.

The 1,2-H and, to a lesser extent, the 1,2-C migrations are the most common carbenic rearrangements in solution (1-3). Once they were considered too fast for absolute kinetic studies, but the advent of laser flash photolysis (LFP) in the 1980's (4), and the introduction of the ylide methodology to follow the reactions of carbenes that lack useful UV absorptions of their own (5,6), have opened wide the portals of investigation (7).

In this paper, we will first introduce aspects of LFP methodology by examination of the absolute kinetics of cyclopropylchlorocarbene rearrangements. Next, we will consider the kinetic modulations induced by "spectator" substituents (i.e., X in R-C-X). A discussion of the activation parameters of these rearrangements will follow, with emphasis on the strongly expressed entropic control of the kinetics. We will conclude with discussions of the intervention of precursor excited states and kinetic isotope effects.

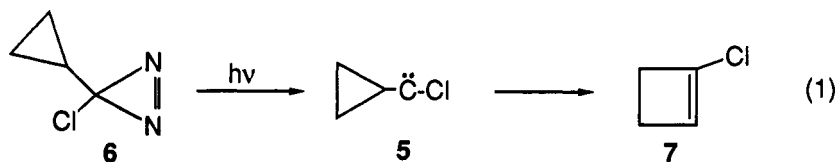### KINETICS OF CARBENIC REARRANGEMENTS

Examples of the 1,2-rearrangements of "simple" carbenes are found in the reactions of dimethylcarbene (**1**), methylchlorocarbene (**2**), benzylchlorocarbene (**3**), isopropylchlorocarbene (**4**), and cyclopropylchlorocarbene (**5**). Carbenes **1-4** afford 1,2-H shifts with rate constants ranging from $1-3 \times 10^6$ s^{-1} for **2** (8-10) to $>10^8$ s^{-1} for

$$CH_3\text{-}\ddot{C}\text{-}CH_3 \qquad CH_3\text{-}\ddot{C}\text{-}Cl \qquad PhCH_2\text{-}\ddot{C}\text{-}Cl \qquad (CH_3)_2CH\text{-}\ddot{C}\text{-}Cl \qquad \triangleright\text{-}\ddot{C}\text{-}Cl$$

$$\textbf{1} \qquad\qquad \textbf{2} \qquad\qquad \textbf{3} \qquad\qquad \textbf{4} \qquad\qquad \textbf{5}$$

1 (8,10,11,12) and **4** (8,10), whereas **3** displays an intermediate rate constant, $k \sim 5\text{-}6 \times 10^7$ s^{-1} (8,13). Low activation energies are associated with these reactions [<2.4 kcal/mol for **4** (8,10) to ~4.9 kcal/mol for **2** (10)], with unexpectedly negative entropies of activation; the preexponential factor (log A) for the 1,2-H shift of **2** to chloroethene is only 9.7 s^{-1} (10).

Even this limited set of data points to 2 mechanistic themes associated with 1,2-H shifts: halogen substitution at the carbenic center slows the reaction (compare **2** with **1**), and branching or phenyl substitution at the migration origin accelerates the H shift (compare **4** or **3** with **2**). The latter point is consistent with the hydride-like nature of the 1,2-H shift, in which partial positive charge is imposed on the migration origin, where it can be stabilized by appropriate substitution.

The rearrangement of **5** exemplifies a highly efficient 1,2-C shift. Photolysis of low concentrations of diazirine precursor **6** affords a near quantitative yield of chlorocyclobutene **7** via ring expansion of carbene **5**; see eq. (1). LFP (XeF excimer laser, 351 nm, 14 ns pulse, isooctane, 20 °C) visualizes the carbene at 246 nm, an absorption previously observed by N$_2$-matrix photolysis of **6** at 14 K, which gave **5** with λ_{max} 240 nm, $\varepsilon \sim 10^4$ (14). From the time dependent disappearance of the carbene absorption, we obtain $k = 9 \pm 1 \times 10^5$ s^{-1} for the 1,2-C shift of **5** to **7**.

$$\overset{\triangle}{\underset{Cl}{\bigtimes}}\overset{N}{\underset{N}{\parallel}} \quad \xrightarrow{\ h\nu\ } \quad \triangleright\text{-}\ddot{C}\text{-}Cl \quad \longrightarrow \quad \square\overset{Cl}{} \qquad (1)$$

$$\textbf{6} \qquad\qquad\qquad \textbf{5} \qquad\qquad\qquad \textbf{7}$$

This "direct" determination of $\underline{k}$(1,2-C) was buttressed in 2 ways. Firstly, LFP of **6** in isooctane containing pyridine gave ylide **8** (λ_{max} 370 nm) from the reaction of **5** with pyridine. The observed rate constant for the formation of **8** was linear in [pyridine]. The slope of this correlation gave $\underline{k}_y$ = 7.4×10^8 $M^{-1}s^{-1}$ for the carbene/pyridine reaction, while the Y-intercept at [pyridine] = 0, $\underline{k}$ = 1.5×10^6 s^{-1}, was taken as the composite rate constant for all those reactions that destroy the carbene in the absence of pyridine (5,6). Since the **5→7** rearrangement occurred in high yield, we could take 1.5×10^6 s^{-1} as k(1,2-C), in reasonable agreement with the direct determination (14).
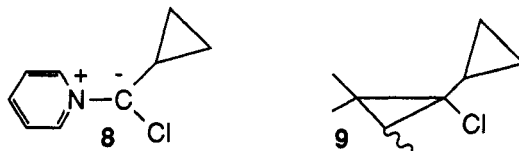
Secondly, we determined the rate constant for the addition of **5** to trimethylethylene, affording **9**, as 6×10^6 $M^{-1}s^{-1}$. With this value, and an analysis of the addition to rearrangement product ratio (9/7), obtained when **5** was generated in the presence of 0.3 M trimethylethylene in isooctane, we could extract $\underline{k}$(1,2-C) = 1.2×10^6 s^{-1}, again in good agreement with the directly determined value (14).

While our work was in progress, Liu and Bonneau described their own studies of the **5→7** rearrangement, reporting $\underline{k}$(1,2-C) = 3.8-6.0×10^5 s^{-1} (8), with the slower value corrected for dimerization of the carbene (not observed under our conditions). From the temperature dependence of the rate constant, tracked via the pyridine ylide method, they determined $\underline{E}_a$ = 7.4 ± 0.2 kcal/mol and log $\underline{A}$ = 11.1 ± 0.1 s^{-1} (15).
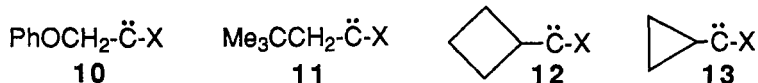
Our own scrutiny of the **5→7** activation parameters led to different results (16). We followed the temperature dependence of k(1,2-C) from 245-309 K by 4 independent methods: (1) directly by LFP observation of the carbene; (2) indirectly via the pyridine ylide; (3) indirectly by the addition of **5** to $MeEtC=CH_2$, using the alkene analogously to pyridine in the ylide technique; and (4) from $\underline{k}_{addn}/\underline{k}_{rearr}$ (product analysis) and $\underline{E}_a$ = 0.74 kcal/mol, directly determined for the addition of **5** to $MeEtC=CH_2$, we obtained $\underline{E}_a$(rearr). All 4 methods gave similar results, with $\underline{E}_a$~2.7-3.8 kcal/mol and log $\underline{A}$ = 8.1-8.7 s^{-1}; the average values were $\underline{E}_a$ = 3.2 ± 0.4 kcal/mol and log $\underline{A}$ = 8.2 ± 0.2 s^{-1}. In Eyring terms, ΔG^* ~ 9 kcal/mol, ΔH^*~2-3 kcal/mol, and ΔS^*~-20 to -24 e.u. Entropic control of this rearrangement is very strongly expressed. Our results (16) differ importantly from those of Liu and Bonneau (15) in the roles of enthalpy and entropy; the ΔG^* values are similar, but the $\Delta H^*/\Delta S^*$ partition markedly varies. Our measurements, confirmed by 4 independent methods, indicate that a very negative ΔS^* is principally responsible for the "slow" **5→7** rearrangement.

We now proceed to a closer examination of the 2 themes that have thus far emerged: the kinetic effects of "spectator" substituents (X) on the 1,2-rearrangements of R-C-X, and the unusual entropic control of at least some of these rearrangements.

SUBSTITUENT EFFECTS ON 1,2-SHIFTS

High level ab initio calculations lead to these predictions of the activation energy barriers for the 1,2-H shifts of carbenes Me-C-X as a function of X (17): (X=) H, 0.5; Cl, 11.5; F, 19; and OMe (trans-Me-C-OMe), 27 kcal/mol. An excellent linear relation exists between $\underline{E}_a$ and the resonance electron donating power of X, expressed as $\sigma_R°$; the better donors decrease the electrophilicity of the carbenic p orbital (the migration terminus), raise the activation energy of the 1,2-H shift, and slow down the rearrangement.

How do experimentally relevant kinetic substituent effects compare with the calculations? Results are available for several series of carbenes, R-C-X, where X varies between F, Cl, and OMe; these include carbenes **10-13** (18-21). Carbenes **10-12** support 1,2-H shifts with the following depencences on X: for **10**, $\underline{k}$(1,2-H) = 3.6×10^7 s^{-1} (X=) Cl;

$$PhOCH_2\text{-}\ddot{C}\text{-}X \qquad Me_3CCH_2\text{-}\ddot{C}\text{-}X$$
10   **11**   **12**   **13**

1.3×10^7 s^{-1}, F; and $\leq1\times10^4$ s^{-1}, OMe (18,19). For **11**, $\underline{k}$(1,2-H) = 1.4×10^7 s^{-1}, (X=) Cl; 2.6×10^6 s^{-1}, F; and $\leq1\times10^4$ s^{-1}, OMe (18,19). For **12**, $\underline{k}$(1,2-H) = 1.2×10^7 s^{-1} (X=) Cl; and 5.3×10^5 s^{-1}, F (18,19). From these results, we derive $\underline{k}$(1,2-H) kinetic ratios for R-C-Cl vs. R-C-F of 2.8, 5.4, and 23, respectively, for carbenes **10**, **11**, and **12**. These ratios appear to be much lower than anticipated, based on a differential $\underline{E}_a$ of ~7 kcal/mol (17). On the other hand, analogous ratios for R-C-F/R-C-OMe for carbenes **10** and **11** appear to exceed 250-1000.

Parallel observations can be made for the 1,2-C shifts of carbenes **12** and **13**. With **13**, k(1,2-C) = 9.0×10^5 s^{-1}, (X=) Cl; 1.4×10^5 s^{-1}, F; and $\leq 3 \times 10^3$ s^{-1}, OMe (18,21); while, for **12**, k(1,2-C) values are 5.6×10^7 s^{-1}, Cl; and 2.1×10^7 s^{-1}, F (18,20). Again, substitution of F for Cl seems to have only a modest effect on the rate of rearrangement, whereas the OMe for F replacement depresses the rate constant substantially. We can conclude that the order of effectiveness of the spectator substituents in slowing 1,2-H or 1,2-C shifts [MeO>>F>Cl] is in keeping with theoretical expectations, although the degree of quantitative agreement is still unclear. We also note the stabilizing effect of the cyclopropyl group of **13**, relative to the cyclobutyl group of **12**. Ring expansions are 60-150 times slower in **13**, where the cyclopropyl "σ" bonds interact strongly with the carbenic p orbital (14).

ENTROPIC CONTROL OF CARBENIC REARRANGEMENTS

We have seen that the rate of the 1,2-C shift of **5→7** is "controlled" by a very unfavorable entropy of activation (16). Similar phenomena attend the 1,2-H shifts of neopentylfluorocarbene, **11-F** (E_a = 3.3 kcal/mol, log A = 8.9 s^{-1}, ΔS^* = -19.8 e.u.) (18), and Me-C-Cl, **2** (log A = 9.7 s^{-1}, ΔS^* = -16 e.u.)(10). A significantly negative activation entropy also attends the 1,2-C shift of **13-F**, cyclopropylfluorocarbene (E_a = 4.2 kcal/mol, log A = 8.3 s^{-1}, ΔS^* = -22.5 e.u.) (18). How are these unusual entropic effects to be understood?

The negative ΔS^* of the cyclopropylhalocarbene 1,2-C ring expansion probably derives from the topology of the free energy surface. Although the barrier is not high, the pass over it may be narrow and steep-walled; the transmission coefficient is low ($\sim 10^{-3}$) due to geometric constraints on the tethered migrant CH_2 group (22,23) and the necessarily correlated motions of C: and CH_2. Many energetically acceptable collisions do not channel energy into motion along the reaction coordinate, so that a large negative ΔS^* of dynamic origin results (16).

Similarly, Modarelli and Platz estimated $\Delta S^* \sim$ -17 e.u. for the 1,2-H shift of Me-C-H to ethylene, attributing the unusual ΔS^* to the need for the migrant H to make a 90° turn away from its original trajectory after reaching the transition state. This leads to inefficient passage over the free energy barrier and a low transmission coefficient in the Arrhenius preexponential term (24).

Quantum mechanical tunneling may also contribute to the large negative ΔS^* value (24-26). The 1,2-H or 1,2-D shifts of CH_3-C-Cl ($\Delta S^* \sim$ -16 e.u.) and CD_3-C-Cl exhibit an unusual temperature dependence of the kinetic isotope effect (k_H/k_D) that may signal a significant incursion of tunneling in the H shift (25). Theoretical analysis supports this contention, and brings observed and calculated (-14.9 e.u.) values of ΔS^* into agreement (26). In fact, the tunneling correction (which is larger for D than for H) appears to enhance the rate constant for the 1,2-H shift by ~10-fold near ambient temperature, and makes much larger, dominant contributions at very low temperatures. Isotope effects will be discussed in greater detail below.

EXCITED DIAZIRINES IN CARBENIC REARRANGEMENTS

To further probe the cyclopropylchlorocarbene rearrangement, we generated the dimethyl derivative, **14**, by both LFP and preparative photolyses of the appropriate diazirine precursor, eq. (2) (27). Using the pyridine probe method (5), and correcting for product formation from excited diazirine (see below), we obtained rate constants for the competitive CH_2 or CMe_2 1,2-C rearrangements of **14**: k(CH_2) = 1.3×10^6 s^{-1} and k(CMe_2) = 2.5×10^5 s^{-1}. The 5-fold preference for CH_2 vs. CMe_2 migration was attributed to reduced steric interference operative in the transition state corresponding to CH_2 migration (27).
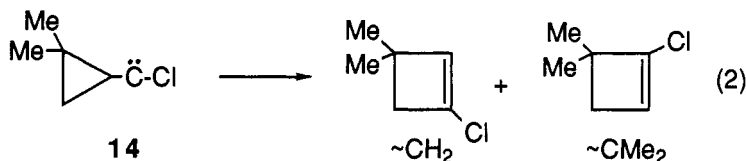
Significantly, the cyclobutenes were accompanied by 18-19% of a 1:1 mixture of $Me_2C=CH_2$ and $ClC≡CH$, the apparent fragmentation products of **14** (27). Moreover, the yield of these fragmentation products did not decrease when the photolysis of the diazirine precursor of **14** was carried out in 9 M trimethylethylene in pentane, where almost all of the **14** was trapped by cycloaddition. It seems reasonable, therefore to attribute the acetylenes to fragmentation, not of the carbene, but of its electronically excited precursor diazirine. Indeed, thermolytic generation of **14** from the diazirine at 60-80 °C, where the excited diazirine should not be accessed, reduced fragmentation to 1-2%.

How widespread is the incursion of excited diazirine chemistry into traditional "carbene" reactions? Platz et al. have made a strong case that photoinitiated alkylcarbene and alkylhalocarbene reactions are often contaminated with reactions of their excited state precursors (12, 24, 28, 29). They found that the yields of pyridine-trappable carbenes from diazirine photolyses varied directly with the bond dissociation energies (BDE) of substituents on the carbon atom α to the diazirine ring (procarbene) carbon atom. This implies that, when (e.g.) a diazirine's α-H atom has a low BDE, it may undergo 1,2-shift cojointly with the expulsion of nitrogen from the photoexcited diazirine, so that some of the "carbene" rearrangement product is formed without intervention of the carbene. Indeed, the excited diazirine faces several choices: N_2-loss with rearrangement; simple N_2-loss to the carbene, which may then rearrange; or fluorescence back to ground state diazirine. The fluorescence can sometimes be observed, and it increases with increasing BDE, for example, upon D for H substitution at the α-carbon (12, 28, 29).

We have also encountered phenomena that are well-explained by the intervention of carbene-mimetic excited state diazirine reactions. Consider, for example, the competitive 1,2-H and 1,2-C rearrangements of cyclobutylchlorocarbene, 12-Cl; cf., eq. 3 (20, 30). In the presence of an olefinic carbene trap, some 12-Cl will be

$$ \text{(3)} $$
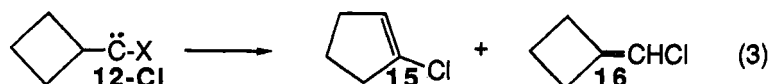
diverted to the addition product. If only the carbene were the precursor of both the addition and rearrangement products, then a plot of the addition/rearrangement (Ad/Re) product ratio would be linear with [olefin]; i.e., [Ad]/[Re] = (k_{ad}/k_{re})[olefin]. However, curved correlations were observed with either tetramethylethylene or trimethylethylene traps (20), demanding the intervention of a second precursor for the intramolecular products 15 and 16. This type of kinetic test was first applied by Tomioka and Liu (31).

The second intermediate is not defined by the kinetics; it could be a carbene/alkene complex (31), an excited carbene (32), or the excited diazirine (33). Choosing the latter, application to the reactions of 12-Cl leads to Scheme 1.

Scheme 1
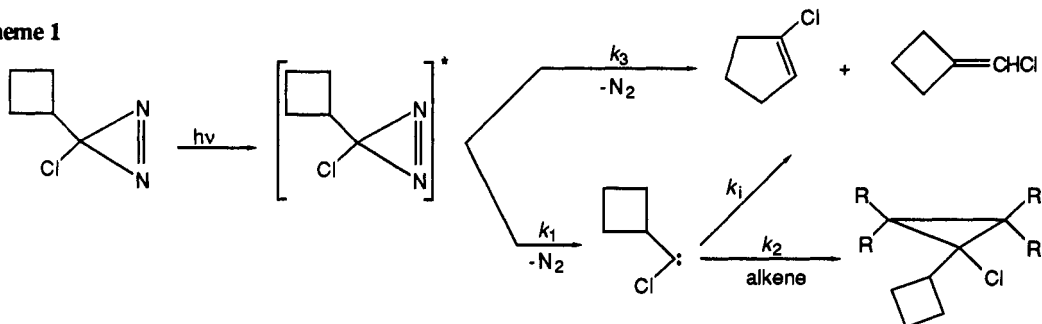
The kinetic relations of this scheme lead to eq. 4, which affords 2 important results:

$$ \text{Re} / \text{Ad} = k_3 / k_1 + \left[k_i (k_1 + k_3) \right] / k_1 k_2 [\text{olefin}] \qquad (4) $$

it predicts that a plot of Re/Ad should be linear in 1/[olefin]; and it indicates that its Y intercept should give k_3/k_1, the rate constant ratio for direct rearrangement from the excited diazirine vs. N_2 loss with carbene formation.

In fact, photolysis of cyclobutylchlorodiazirine in trimethylethylene/pentane gives the products shown in Scheme 1, and follows the kinetic form of eq. 4; the correlation is indeed linear, $r = 1.00$. Taking the observed Y-intercept (1.61±0.12) as k_3/k_1, means that 62% of rearrangement products 15 and 16 come from the excited diazirine; only 38% stems from carbene 12-Cl (20). At 7.55 M trimethylethylene, where almost all 12-Cl should be trapped and the rearrangement products must very largely come from the excited diazirine, 15/16 (~C/~H) = 1.60, representing the product partition of excited diazirine. At [olefin] = 0, 15/16 = 2.23, representing the 62:38 blend of the products from excited diazirine and carbene. From these data, we can extract 15/16 ~ 4.8 for the rearrangement of carbene 12-Cl above.

From this "corrected" product ratio, and with a measured LFP pyridine ylide rate constant for the overall rearrangement of 12-Cl [k(1,2-C) + k(1,2-H)] = 6.8×10^7 s^{-1}, we obtained k(1,2-C) = 5.6×10^7 s^{-1} and k(1,2-H) = 1.2×10^7 s^{-1} for the individual rearrangement paths of the carbene, corrected for incursion of excited diazirine.

A similar treatment applied to the analogous chemistry of carbene **12-F** gave only ~12% of excited state diazirine incursion and 88% of carbene parentage of the products (20). Here, corrections to the 1,2-C and 1,2-H rate constants derived from direct partition of the overall rearrangement rate constant (18) proved to be unnecessary (20). R-C-F is more stable than the analogous R-C-Cl, and presumably is formed more rapidly and efficiently from an excited diazirine precursor, relative to product-forming rearrangement/N_2 loss from the latter. Accordingly, photolyses of alkylfluorodiazirines lead to alkylfluorocarbene products with little excited diazirine contamination. Platz has reached a similar conclusion (29).

An interesting case is the photolysis of t-butylchlorodiazirine (**34**), where we observe an unusually strict product partition between the excited diazirine, which undergoes cojoint N_2 loss and 1,2-Me migration, and the derived carbene, which affords a 1,3-CH insertion product; cf., eq. 5 (**35**). In accord with this scenario, the yield of 1,2-C shift product **17** remains constant at ~9%, and is independent of an added alkene trap (2-methyl-1-butene). Even at 4 M alkene, where 72% of the product mixture is carbene/alkene adduct, the yield of **17** is 8.8%.

$$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (5)$$

On the other hand the ratio Ad/Ins is linearly dependent on [alkene]. The 1,2-Me shift to **17** comes only from the excited diazirine, whereas insertion product **19** comes only from carbene **18**. However, when the diazirine is subjected to thermolysis at 79 °C, both products come from the carbene, with little involvement of excited diazirine; a 9:1 distribution of **19/17** is observed, and both products decrease in constant proportion upon alkene addition (35).

The rate constant for the 1,3-CH insertion of **18** to **19** is ~9×10^5 s^{-1} (21 °C), as measured by the pyridine ylide method (34, 35). At very low temperatures (11-30 K) in a nitrogen matrix carbene **18** affords insertion product **19** by a tunneling process (36). The contribution of tunneling to the insertion reaction at intermediate temperatures and in solution is unknown, but will be probed in our laboratory with the aid of kinetic isotope effects.

KINETIC ISOTOPE EFFECTS

Kinetic isotope effects (KIE) attending carbenic 1,2-H(D) shifts were initially found to be small, in accord with the intuitive belief that the corresponding, low activation energy transition states would be "early," with relatively little concomitant C-H bond stretching. Thus, k_H/k_D for the 1,2-H vs. 1,2-D shifts of ArCHD-C-Me ranged from 1.2-1.6 (37), and the initially reported KIE for the rearrangements of $CH_3(D_3)$-C-Cl was also small ($\leq$1.3) (10). However, the latter KIE ranged from 0.9 at 248 K to 1.8 at 343 K, as determined by LFP, with tunnelling suggested to play a major role (25). Tunneling rationalized the observed curved Arrhenius plots, the increase of k_H/k_D with increasing temperature, and the very negative ΔS^* (25).

Theoretical analysis supports the occurrence of tunneling in the latter case and offers further insights. Firstly, tunneling becomes dominant in the rearrangement of CH_3-C-Cl only below 200 K; above 200 K, the classical rate exceeds that due to tunneling. Secondly, the computed transition state is surprisingly "late," with the migrant H approximately equidistant between the origin and terminus (26). Tunneling has also been experimentally implicated in the 1,2-H shifts of Me-C-H (24) and PhCH$_2$-C-Cl (38), as well as in the 1,3-CH insertion of Me$_3$C-C-Cl (36).

We examined the KIE's associated with the 1,2-H(D) shifts of the neopentylhalocarbenes, **11**, X=Cl or F (39, 40). Generation of **11-F** by photolysis of neopentylfluorodiazirine (or its α,α-d_2 analogue) could be shown to involve no more than 4-6% of H(D) shift contamination from the excited diazirine; the olefinic products were overwhelmingly derived from the carbene (39). Therefore, the KIE associated with the H(D) shifts of **11-F-α-d_1** could be determined from the appropriate product distributions, which were readily obtained by 200 MHz NMR analysis of the well-separated vinyl proton resonances (39); cf., eq. 6. At 22 °C the KIE's were $(k_H/k_D)_Z$ = 5.2 and $(k_H/k_D)_E$ = 4.8, whereas, at -30 °C the corresponding KIE's were 6.1 and 6.2.

$$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (6)$$

As a check on these surprisingly large values, we also used LFP to measure the absolutie rate constants for the individual 1,2-H and 1,2-D shifts of **11-F** and **11-F-α-d_2**. In pentane at 20 °C, these were 2.6×10^6 s^{-1} (d_0) and 4.0×10^5 s^{-1} (d_2), leading to k_H/k_D = 6.5($\pm$1.0), in good agreement with the "intramolecular" KIE determined via eq. 6 (39).

These KIE's are large, but their modest and directionally normal temperature dependences make them consistent with classical transition states. A large KIE (3.2) has also been observed for the comparative lifetimes of CH_3-C-CH_3 vs. CD_3-C-CD_3 (12).

From the classical perspective, one would anticipate a smaller KIE for the 1,2-H(D) shift of the more reactive neopentylchlorocarbene, **11-Cl**, relative to **11-F**. This study is more complicated than that of **11-F** because products derived directly from the excited diazirine make a 10-fold larger contribution (40-60%) with neopentylchlorodiazirine than with neopentylfluorodiazirine (6%) (40). Indeed, the excited diazirine contribution is reduced to 24-28% in the case of neopentylchlorodiazirine-α-d_2, indicating an apparent KIE on the partition of the excited diazirine between direct rearrangement and N_2 loss to the carbene. Platz has put analogous effects to good use in his studies of the methylcarbenes (12, 24).

The pyridine probe LFP method follows only the carbene, not the excited diazirine which does not live long enough to react with pyridine (5, 29). We could thus determine the rate constants (pentane, 20 °C) for the 1,2-H(D) shifts of Me_3CCH_2-C-Cl (k_H = $1.4\pm0.2\times10^7$ s^{-1}) and Me_3CCD_2-C-Cl (k_D = $4.0\pm0.3\times10^6$ s^{-1}), leading to k_H/k_D = 3.5$\pm$0.6 (40). An "intramolecular" (product analysis) KIE determined from <u>thermolytically</u> generated Me_3CCHD-C-Cl gave k_H/k_D = 2.6 at 60 °C in $CDCl_3$ (40). Note that the KIE's for **11-Cl** are sizeable, although smaller than those observed with **11-F**. Moreover, their temperature dependence from 20° to 60° is normal.

Interestingly, there is a <u>comparable</u> KIE operating in the direct 1,2-H(D) shifts of the excited diazirine precursor of Me_3CCHD-C-Cl. In neat (9.2 M) 2-methyl-1-butene, where >95% of any generated carbene should be trapped by addition, photolysis of the α-d_1 diazirine gives $Me_3CCHD=CHCl$ and $Me_3CCH=CDCl$ in a ratio of 2.83$\pm$0.14, which can be taken as k_H/k_D for the excited diazirine, a value that is similar to the KIE of the corresponding carbene, **11-Cl**.

In contrast to CH_3-C-Cl, where KIE is small, increases with increasing temperature, and tunneling is important (25, 26), the KIE's for **11-F** and **11-Cl** are large and (in limited studies) decrease with increasing temperature (39, 40). One inference is that the latter cases are classical; i.e., tunneling is unimportant. Alternatively, tunneling will become important only at very low temperatures (<200 K) in solution, or in very cold matrices. These possibilities await investigation. Normally, we would expect very high values of k_H/k_D when tunneling becomes important, as in the 1,2-H(D) rearrangement of $PhCH_2(D_2)$-C-Cl (38) or in the 1,3-CH(CD) insertion reaction of Me_3C-C-Cl (36). However, the very low KIE observed for Me-C-Cl, where tunneling does appear to intrude (25, 26), suggests that we still have much to learn in order to construct a complete and satisfying analysis.

Despite the unusual primary KIE's observed in the alkyl- and alkylhalocarbene rearrangements, the α-secondary KIE expressed in the CH_2/CD_2 competitive ring expansion of (2,2-dideuteriocyclopropyl)chlorocarbene is normal.
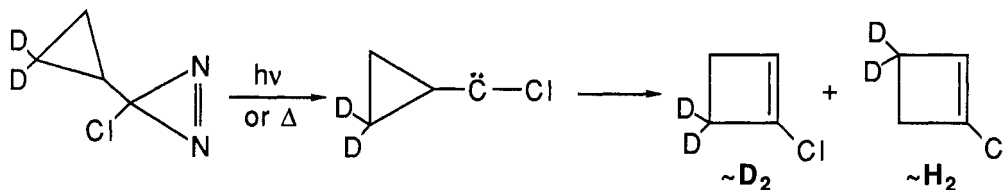
The observed KIE, 1.2 at 21 °C, agrees with the ab initio calculated value, 1.12, and must largely originate in hybridization changes (sp$^{2.6}$ to sp$^{2.4}$) at the migrating carbon atom. Differential steric or charge effects were calculated to be unimportant in the alternative rearrangement transition states (41).

Summarizing, present "wisdom" concerning carbenic KIE's indicates that they can be surprisingly large, that the transition states for 1,2-H(D) shifts may not be as "early" as previously supposed, that tunneling may dominate at least some 1,2-H(D) migrations and actually reduce the KIE if the tunneling correction is larger for D than for H, and that (in the latter case) one may observe a decreasing KIE with decreasing temperature. Finally, when the carbenes are generated by the photolysis of diazirines, the rearrangement products may be formed from both the carbene and from the excited diazirine, with significant KIE's also operating in the direct rearrangement of the excited diazirine. Present wisdom, of course, is often transitory.

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