Mechanisms of Acid Decomposition of Dithiocarbamates. 1. Alkyl Dithiocarbamates

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The acid decomposition of some substituted methyldithiocarbamates was studied in water at 25 °C in the range of H_o −5 and pH 5. The pH−rate profiles showed a bell-shaped curve from which were calculated the acid dissociation constants of the free and conjugate acid species and the specific acid catalysis rate constants k_H. The Brønsted plot of k_H vs pK_N, the dissociation constant of the conjugate acid of the parent amine, suggests that the acid cleavage occurs through two mechanisms that depend on the pK_N. The plot presents a convex upward curve with a maximum at pK_N 9.2, which is consistent with the cleavage of the dithiocarbamate anion through a zwitterion intermediate and two transition states. For pK_N < 9.2, the N-protonation is slower than the C−N bond breakdown. Inverse SIE showed that the zwitterion is formed through a late transition state. At pK_N > 9.2, the C−N bond breakdown is the slowest step, and according to the inverse SIE, the transition state changes rapidly with the increase of pK_N to a late transition state. The plot shows a minimum at pK_N ~10, indicating that a new mechanism emerges at higher values, and it is postulated that it represents a path of intramolecular S to N proton-transfer concerted with the C−N bond breakdown. The thiocarbonyl group acts as a powerful electron-withdrawing group, decreasing the basicity of the nitrogen of the parent amine by 14.1 pK units.

Introduction

Several dithiocarbamates, in particular, ethylene bis-(dithiocarbamate) metallic salts (Zn, Mn, Cu, Fe), are well-known fungicides. However, their mechanisms of action upon fungi are speculative[1] because their mechanisms of decomposition, depending on the basicity of the amine, have not been studied in detail[2] (eq 1). The

$$R\text{-}NHC\overset{S}{\underset{SH}{\diagup}} \longrightarrow RNH_2 + CS_2 \qquad (1)$$
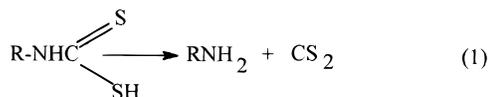
reaction of acid cleavage has been postulated to occur through a concerted intramolecular S to N hydron transfer and C−N bond breakdown[3,4] and (or) through a zwitterionic intermediate.[5–8] Also, in some cases, general acid catalysis has been observed,[2,4] whereas in other examples it was not detected.[8,9] Previous works on carbamates[10–12] and monothiocarbamates[8] have studied the effect of amine basicity on the reaction rate, general acid catalysis of the expulsion of weakly basic amines, and the rate of protonation of the leaving nitrogen, which is kinetically significant in some of these reactions.

N-Alkyldithiocarbamic acids are relatively stable, and the kinetics of their decomposition can be measured in a wide pH range. At the same time, the UV spectra of the species formed at different acidity of the medium can be observed, allowing in some cases the acid dissociation constants to be determined directly.

In this work, we studied the pH−rate profiles of the acid decomposition of substituted methyldithiocarbamates in order to characterize the dependence of the rate constants on the basicity of the parent amine and the mechanisms involved. The acid cleavage of aryl and cycloalkyldithiocarbamates is different,[8] and they will be studied in subsequent papers.

Experimental Section

All reagents were of analytical grade. Amines were distilled before use or crystallized as ammonium salts. Carbon disulfide was purified over metallic mercury and phosphorus pentaoxide followed by distillation.[13] The absorptivity of carbon disulfide in ethanol at 314 nm was found to be 44.4 cm$^{-1}\cdot$M^{-1}.

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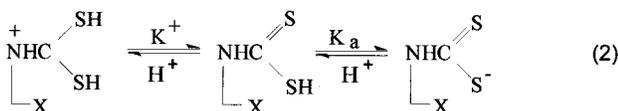(13) Brauer, G., Ed. *Handbook of Preparative Inorganic Chemistry*; Academic: New York, 1963; Vol. 1, p 652.

Table 1.   Dissociation and Rate Constants Related to the Acid Cleavage of S-Substituted Methyldithiocarbamates in Water at 25 °C[a]

RCH$_2$NHC(S)SH

no. order	R	σ_I	pK^+	pK_a	pK_N	$10^4 k_o$, s^{-1}	k_H, M^{-1}·s^{-1}
1	CF$_3$	0.42[b]	−1.81[c]	1.55[c]	5.70[d]	172 ± 10	0.61 ± 0.05
2	CH$_2$NH$^+_3$	0.36[b]	−5.60[c]	2.00[c]	7.52[d]	20.9 ± 0.2	0.21 ± 0.01
3	C$_6$H$_5$	0.10[b]	−4.5[e]	2.69[f]	9.35[g]		
4	CH$_2$OMe	0.07[b]	−4.50[c]	2.85[c]	9.20[d]	18.2 ± 0.6	1.29 ± 0.07
5	CH$_2$OH	0.05[b]	−4.65[c]	2.82[c]	9.50[d]	15.2 ± 0.2	1.00 ± 0.09
6	NH$_3^+$(CH$_2$)$_5$	0.00[f]	−4.20[c]	2.95[c]	9.94[h]	3.2 ± 0.1	0.29 ± 0.02
7	H	0.00[b]	−3.9[e]	2.89[e]	10.67[g]		
8	C$_3$H$_7$	−0.03[b]	−4.08[i]	3.02[f]	10.59[d]		0.35[j]
9	CH$_3$	−0.05[b]	−4.10[e]	3.05[e]	10.70[g]	4.78 ± 0.04	0.54 ± 0.02

[a] This work unless indicated; pK_N:pK_a of the parent amine. [b] Reference 15a. [c] From the pH−rate profile. [d] Kortum, G., Vogel, W., Andrussow, K., Eds. *Dissociation Constants of Organic Acids in Aqueous Solution*; IUPAC-Butterworths: London, 196. [e] Reference 5. [f] Extrapolated from eq 3. [g] Perrin, D. D. *Dissociation Constants of Organic Bases in Aqueous Solution*; Butterworths: London, 1965. [h] Extrapolated from the series H$_3$N$^+$(CH$_2$)$_n$N$^+$H$_3$, for n = 6. [i] Extrapolated from eq 4. [j] Reference 8.

The dithiocarbamates were obtained at room temperature from the aqueous solution of the corresponding amine, adding equimolar amounts of carbon disulfide.[2a,8,14] In order to have the amine as the free base, a small excess of sodium hydroxide was added. The *N*-(2-aminoethyl) and *N*-(6-amino-*n*-hexyl)dithiocarbamate sodium salts were prepared from a solution of the amine buffered at pH 9.5 with sodium carbonate. All dithiocarbamate salts were crystallyzed in ethanol, except the *N*-(2-hydroxyethyl)dithiocarbamate, which was a syrup.

Acid Dissociation Constants. The pK^+ and pK_a (eq 2) of the substituted methyldithiocarbamates were in general calculated from the pH−rate profiles of the acid decomposition (see below). The experimental values of pK^+ = −4.1 and pK_a = 3.05,[5,14c] of ethyl dithiocarbamate coincided with the kinetically-calculated values.

$$\underset{X}{\overset{SH}{\underset{|}{NHC}}}{\overset{SH}{\overset{+}{}}} \underset{H^+}{\overset{K^+}{\rightleftharpoons}} \underset{X}{\overset{S}{\underset{|}{NHC}}}{\overset{}{SH}} \underset{H^+}{\overset{K_a}{\rightleftharpoons}} \underset{X}{\overset{S}{\underset{|}{NHC}}}{\overset{}{S^-}} \qquad (2)$$

Kinetics. The decomposition of the dithiocarbamate in water was followed spectroscopically in the region of 270−280 nm at 25 °C on a Cary 219 spectrophotometer. The initial concentration was ca. 10^{-4} M. The acidity ranged between H_o −4.92 and pH 5. Between pH 2 and 5 the solutions were buffered at least at two buffer concentrations, and no general acid catalysis was observed.

Kinetics were all first order. A generalized minimum least-squares program was used to fit the experimental points to the theoretical curve of the pH−rate profiles.

Results

Acid Dissociation Constants of Substituted Methyldithiocarbamates. Considering the dissociations of the substituted methyldithiocarbamates (eq 2), the LFER between pK_a and σ_I[15,16] was determined from the experimental value of compound **9**,[5] whereas for compounds **2**, **4**, **5**, and **6** the pK_a values were calculated from the pH−rate profiles as shown in eq 3 (Table 1).

$$pK_a = -2.56\sigma_I + 2.94 \quad (n = 5, r = 0.992) \qquad (3)$$

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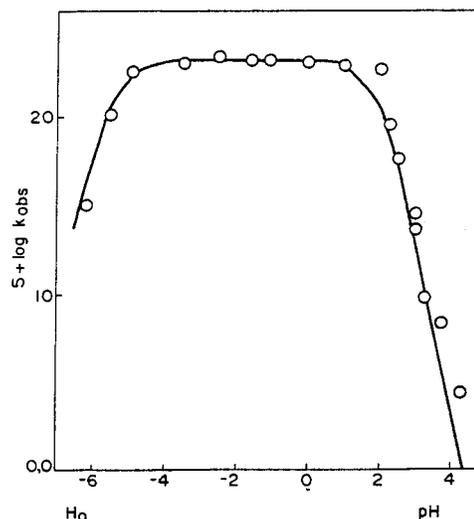

Figure 1. pH−rate profile of the acid decomposition of *N*-(2-aminoethyl)dithiocarbamate in water at 25 °C.

The values obtained from the pH−rate profiles of these same compounds were used to calculate eq 4 for the pK^+ of the conjugate dithiocarbamic acids. Values from the literature for compounds **3**, **7**, and **9** were also used for the calculation.[5]

$$pK^+ = -3.91\sigma_I - 4.20 \quad (n = 7, r = 0.952) \qquad (4)$$

Kinetics of the Decomposition of Substituted *N*-Methyldithiocarbamates. The pH−rate profiles of the acid decomposition of compounds **1**, **4**, **5**, **6**, and **9** in Table 1 present the same bell-shaped curve as the (2-aminoethyl)dithiocarbamate (**2**) shown in Figure 1. The shape might be due to a change in the rate-limiting step caused by the acidity of the medium, or it might also be due to the dissociation of the reactive species. Since the values of pK^+ and the pK_a for methyl and ethyldithiocarbamates (calculated from the pH−rate profile) coincide with the experimental values, the reaction occurs according to Scheme 1, through any of the species SH$_2^+$, SH, or S$^-$. The observed first-order rate constant can be expressed by eq 5, where a_{H^+} = antilog ($-$pH or H_o), and k_o

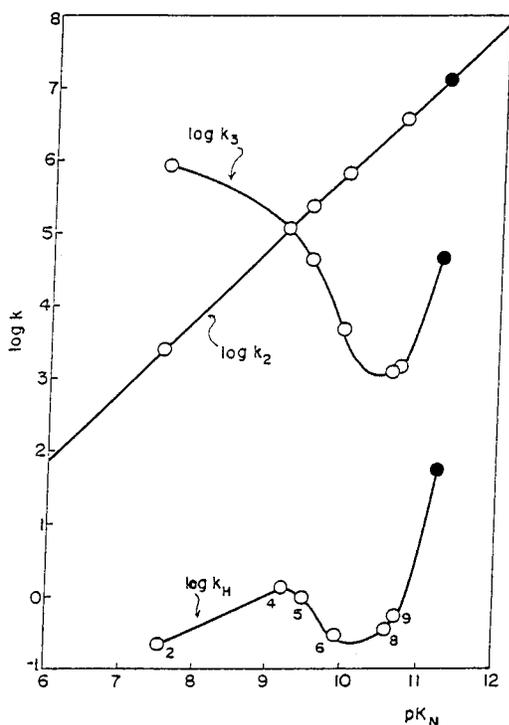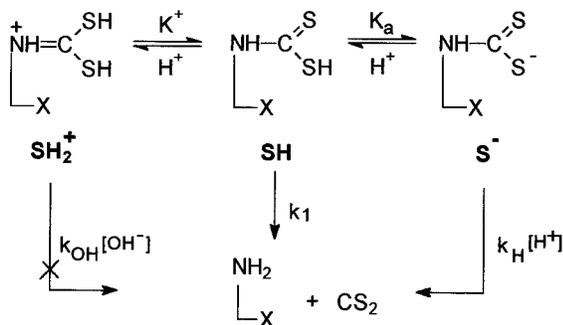$$k_{obs} = \cfrac{k_o}{\cfrac{K_a}{a_{H^+}} + 1 + \cfrac{a_{H^+}}{K^+}} \qquad (5)$$

Figure 2. Brønsted plot of the specific acid catalysis rate constants and the pK_N of the leaving amine for the acid decomposition of substituted methyldithiocarbamates in water at 25 °C: ●, piperidinedithiocarbamate;[8] k_2, rate constant of the N-protonation; k_3, rate constant of the C−N bond cleavage.

Scheme 1

in general is equal to the average value of k_{obs} at the plateau of the profile due to the rather large difference between K^+ and K_a (eq 2). Also, k_0 is kinetically equivalent to $k_{OH} K_W/K^+$, k_1, or $k_H K_a$ depending on which reactive species is actually involved. However, the kinetic alternative of decomposition of the conjugate acid with specific base catalysis has to be disregarded, since k_0 is of the order of $10^{-3}-10^{-4}$ s^{-1}, and consequently k_{OH} should be $10^{14}-10^{17}$ M^{-1} s^{-1}, much larger than the diffusion-controlled rate constant. In Table 1 are shown k_0 and k_H for the series of substituted methyldithiocarbamates, and the Brønsted plot of the specific acid catalysis rate constants k_H vs the pK_N of the parent amine is shown in Figure 2.

(Trifluoroethyl)dithiocarbamate (**1**) presents a pK^+ value that is 4 units higher than expected from eq 4 and also reacts faster than the corresponding DTC with similar pK_N. Several contributions (polar effect, π inductive effect, carbon−fluorine hyperconjugation, 1,3-pp interactions) may affect the behavior of this substituent.[17] Concerning the role of the trifluoromethyl group in the

Table 2. Solvent Isotope Effect for the Acid Decomposition of Some *N*-Alkyldithiocarbamates in Water at 25 °C

	RCH$_2$NHC(S)SH	
R	k_0^D/k_0^H	k_D/k_H
CH$_2$NH$_3^+$	2.21 ± 0.10	2.90 ± 0.13
CH$_2$OMe	2.40 ± 0.14	3.14 ± 0.18
(CH$_2$)$_5$NH$_3^+$	2.33 ± 0.03	3.05 ± 0.04
CH$_3$	3.05 ± 0.10	4.00 ± 0.13

reactivity of aliphatic cations, information is too scarce to provide a confident explanation of the increase of pK^+ and k_H for the acid decomposition of **1**.[15b,18]

Solvent Isotope Effect. The SIE on k_0 was determined for alkyldithiocarbamates with pK_N from 7.52 to 10.70 (Table 2). Since $k_0 = k_H K_a$, the inverse SIE was calculated from eq 6. Sulfur acids present low isotopic

$$\frac{k_D}{k_H} = \frac{k_0^D}{k_0^H} \cdot \frac{K_a^H}{K_a^D} \qquad (6)$$

fractionation factors (ϕ_{S-L} = 0.40−0.46),[19] giving an average value of 1.31 for the ratio K_a^H/K_a^D,[20] which was considered constant because of the small range of pK_a values of the compounds studied.

Discussion

Brønsted Plot. The maximum in the nonlinear Brønsted-type plot of Figure 2 is a classical piece of evidence for a change in the structure of the transition state of the rate-determining step. The convex upward curve observed in the range of pK_N of 7−10 indicates that the mechanism of cleavage consists of two consecutive transition states that change their effective charge on the nitrogen atom with opposite dependence.[16a,21,22] Up to pK_N = 9.2, the specific acid catalysis rate constant increases in accordance with growth of the positive charge on the nitrogen, while at higher values of pK_N a decrease of that charge favors the cleavage. This type of dependence is consistent with a cleavage of the dithiocarbamate anion through a zwitterion. In this range of pK_N, a concerted mechanism with asynchronous proton transfer and C−N bond breakdown has to be ruled out because of the absence of general acid catalysis and the observed inverse solvent isotope effect. The possibility of this path will be discussed below. At a pK_N value of about 10.2, a minimum of k_H indicates a change of mechanism and the rate increases rapidly with the basicity of the parent amine. These two paths of the decomposition reaction are shown in Scheme 2. Along one route, the anion S$^-$ is protonated on the nitrogen in a specific acid catalysis step and the zwitterion SH$^\pm$ formed decomposes into products. Along the other path, the free dithiocarbamic acid decomposes through a concerted mechanism. Applying steady-state approxima-

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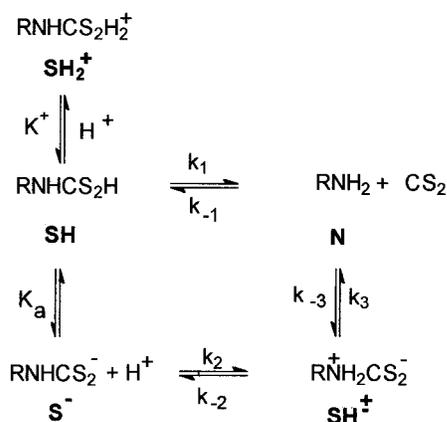
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Scheme 2

$$RNHCS_2H_2^+$$
$$SH_2^+$$

$$K^+ \big\Vert H^+$$

$$RNHCS_2H \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} RNH_2 + CS_2$$

$$SH \qquad\qquad N$$

$$K_a \big\Vert \qquad\qquad k_{-3} \big\Vert k_3$$

$$RNHCS_2^- + H^+ \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} R\overset{+}{N}H_2CS_2^-$$

$$S^- \qquad\qquad SH^{\pm}$$

tion on SH$^\pm$, the rate law of disappearance of the total substrate $S_T = S^- + SH + SH_2^+$ is given by eq 7, where S_o, S_T and $S_{T,\infty}$ are the total concentration of the substrate at zero time, time t, and infinite time, respectively (see the Supporting Information).

$$-\frac{dS_T}{dt} = \left[\frac{k_1 + \dfrac{k_2 k_3 K_a}{k_3 + k_{-2}}}{\dfrac{K_a}{a_{H^+}} + 1 + \dfrac{a_{H^+}}{K^+}}\right](S_T - S_{T,\infty}) -$$

$$\left(\frac{k_{-2}k_{-3}}{k_3 + k_{-2}} + k_{-1}\right)(2S_o - S_{T,\infty} - S_T)(S_{T,\infty} - S_T) \quad (7)$$

When the reaction is carried out under acidic conditions where $a_{H^+} \gg K_N$, the acid dissociation constant of the parent amine, the reverse reaction constants k_{-3} and k_{-1}, are zero, and the experimental rate constant can be expressed by eq 8, which is equivalent to eq 5, where the numerator is k_o. The rate constant of the concerted path

$$k_{obs} = \frac{k_1 + \dfrac{k_2 k_3 K_a}{k_3 + k_{-2}}}{\dfrac{K_a}{a_{H^+}} + 1 + \dfrac{a_{H^+}}{K^+}} \quad (8)$$

is k_1 and the term $k_2 k_3/(k_3 + k_{-2}) = k_H$ represents the specific acid catalysis rate constant of the mechanism of decomposition through the zwitterion. This expression can also be written as eq 9, where $K_\pm = k_{-2}/k_2$ is the acid dissociation constant of the N-protonated zwitterion.

$$k_H = \frac{k_3}{(k_3/k_2) + K_\pm} \quad (9)$$

The pK_N of substituted methylammonium ions is given by eq 10,[15a] and substituents adjacent to the nitrogen

$$pK_N = -8.57\sigma_1 + 10.29 \quad (n = 9, r = 0.997) \quad (10)$$

atom, such as the dithiocarboxylate group CSS$^-$, would cause a constant decrease in pK_N equal to $-8.57\sigma_{CSS}$, where σ_{CSS} is the substituent constant of the dithiocarboxylate. Since this group is conjugated to the nitrogen, it is expected to have a high positive value because it works as an electron sink. For N-protonated alkylcarbamates, $-8.57\sigma_C$ was estimated[8] to be -8.4, or $\sigma_C = +0.95$, for the carboxylate group. When one oxygen atom

is substituted by sulfur, the substituent constant increases to $+1.39$.[8] Considering that the substitution of the second oxygen produces the same effect, the substituent constant of the adjacent dithiocarboxylate group should be $\sigma_{CSS} = +1.80$, and therefore, p$K_\pm$ is expected to be some 15 pK units lower than pK_N. This value indicates that the protonation of water by the zwitterion is thermodinamically favorable and k_{-2} should be of the order of 10^{10} s^{-1},[23,24] allowing an estimation of k_2 and consequently k_3. The ratio k_3/k_2 is much smaller than $K_\pm$, and $k_3 \approx k_H K_\pm$. On the other hand, at the maximum of the Brønsted plot (compound **4**), k_2 should be equal to $k_3 = 1.14 \times 10^5$ s^{-1}, and therefore, p$K_\pm = -4.94$, that is 14.1 pK units lower than pK_N, similar to the value obtained above (eq 11). The experimental values of k_H and the calculated values for k_2 and k_3 are shown in Figure 2.

$$pK_\pm = pK_N - 14.1 \quad (11)$$

The difference of free energy of activation between transition states T$_2$ and T$_3$ is only 3.4 kcal·mol^{-1} for compound **4**. This small difference means that both transition states control the overall reaction rate. The zwitterion intermediate is a high energy and almost a high barrier intermediate. An important consequence of these considerations is that solvent isotope effect experiments will characterize the structure of a virtual transition state with the characteristics of both T$_2$ and T$_3$.

The p$K_\pm$ of the zwitterion is smaller than the solvated proton, so therefore, the proton transfer for N-protonation is thermodynamically unfavorable and general acid catalysis is not expected to be observed, and this was confirmed in our experiments.

According to the calculated values of k_2 and k_3 (Figure 2), the rate of N-protonation is faster than the C–N bond cleavage, up to p$K_N = 9.2$. At higher values of pK_N the last step becomes the slowest. The rate of the C–N bond cleavage decreases steadily to a minimum where pK_N is about 10.5 due to the higher stability of the zwitterion. The curvature of the line of log k_3 vs pK_N suggests a rather fast increase of the C–N bond cleavage at the transition state in a short range of pK_N values. This interpretation is supported by the results of the solvent isotope effect.

The minimum of log k_H followed by a fast increase of the basicity of the amine (Figure 2) characterizes a change of mechanism.[16a,22] It seems that no intermolecular mechanism reasonably accounts for the fast increase of the rate constant of decomposition of the dithiocarbamates with increasing pK_N. Both k_3 and $K_\pm$ decrease as the basicity of N increases. Path 1 in Scheme 2 represents a mechanism of direct intramolecular hydron transfer concerted with the C–N bond breakdown, in a pH-independent process, through the acid form of the dithiocarbamate, which can be acid–base catalyzed by a water molecule. This mechanism, without the predissociation of the dithiocarbamic acid, must be an energetically preferred alternative to the intermolecular protonation of N, when its basicity and also the strength of the C–N bond increases. Basicity of the nitrogen increases faster than the acidity of the thiol sulfur, and

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once the concerted mechanism is preferred, the rate increases rapidly with pK_N.

It has been observed that the delocalization of the nitrogen electron pair into the dithiocarbamate group shortens the C−N bond length, because of the higher double-bond character, and modifies the infrared spectra of dithiocarbamates.[25−27] The barrier of internal rotation about the C−N bond is considerably higher in *N,N*-dialkylthioamides than in *N,N*-dialkylamides, due to the higher double-bond character of the C−N bond.[28−31] The rotation increases in dilute acid and is solvent dependent.[32,33]

To reach the structure of transition state **I**, the C−N bond has to be twisted, thus inhibiting the resonance of


I
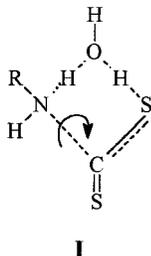
the thiocarbonyl group with the nitrogen and increasing its basicity. The reaction may be catalyzed by a water molecule. The basicity of the nitrogen also increases with the breaking of the C−N double bond until the process of hydron transfer **S** to **N** becomes thermodynamically favorable. The internal rotation barrier of *N,N*-dialkylthioamides is very similar to that observed for the cleavage of dithiocarbamates of strong basic amines, suggesting that the twisting of the C−N bond is an important component of the total kinetic barrier.

Solvent Isotope Effect. The observed SIE of Table 2 is consistent with the proposed mechanisms. Considering that $k_3/k_2 \ll K_\pm$, the inverse solvent isotope effect is given by eq 12 according to the mechanism through the zwitterion (Scheme 2). The ratio $K_\pm^H/K_\pm^D$ is difficult to

$$\frac{k_D}{k_H} = \frac{k_3^D}{k_3^H} \cdot \frac{K_\pm^H}{K_\pm^D} = \left(\frac{k_3^D}{k_3^H}\right)_{sec} \left(\frac{k_2^D}{k_2^H}\right)_{pri} \left(\frac{k_{-2}^H}{k_{-2}^D}\right)_{pri} \quad (12)$$

assess because estimation of ΔpK for strong acids in regions beyond the pK_a of water is rather problematic.[34−38] Since k_3^D/k_3^H is a secondary SIE, consequently small, the observed effect shows that $K_\pm^H/K_\pm^D > 1$, that is, the N-protonation is stabilized in D_2O. The magnitude of the

change of solvent isotope effect observed for compounds **2**, **4**, and **6** must be mainly a consequence of the change of the ratio of $K_\pm^H/K_\pm^D$, which is equal to $(k_2^D/k_2^H)(k_{-2}^H/k_{-2}^D)$. Since k_{-2} is diffusion controlled, with a low barrier to hydron transfer, it does not depend much on $K_\pm$. The rate-limiting step is the encounter of the zwitterion with a water molecule that should be independent of the isotope, and the SIE should be unity, except for the viscosity effect between H_2O and D_2O.[39] Therefore, the ratio $K_\pm^H/K_\pm^D$ reflects essentially the primary solvent isotope effect on the O to N hydron transfer reaction. Approximate values of primary solvent isotope effects for hydron transfer may be obtained through the method described by Schowen.[40] The transition state for the O to N hydron transfer is

$$O\text{-----}\overset{1-\chi}{L}\text{-----}\overset{\chi}{N}$$
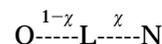
where χ indicates the bond order of the bond being formed. For the initial state ($\chi = 0$) there is no isotope effect. The equilibrium inverse isotope effect (eq 13) is equal to 3.11.[40,41] The maximum primary isotope

$$k_2^D/k_2^H = \frac{K_\pm^D}{K_\pm^H} = \frac{(\phi^2_{O-L})}{(\phi^3_{O^+-L})} \frac{(\phi^2_{N^+-L})}{(\phi_{N-L})} \quad (13)$$

effect $k_2^H/k_2^D = 11.4$ is reached at $\chi_{max} = 0.53$. The plot of k_2^H/k_2^D vs χ gives an inverse SIE only when $\chi > 0.97$, indicating that the transition state T_2 is late or tight in the reaction coordinate of formation of the zwitterion. Since the contribution of the term k_3^D/k_3^H is small and k_{-2}^H/k_{-2}^D is constant, the main contribution to the SIE comes from the primary effect. The inverse SIE increases from compound **2** to compound **4**, suggesting that for compound **2** there is a partial transfer of the hydron at the virtual transition state. If the maximum inverse SIE is obtained at equilibrium ($\chi = 1$) where $k_2^D/k_2^H = 3.11$, the experimental value of 3.14 agrees well for compound **4** and at the same time indicates that the secondary effect due to the C−N bond fission is near unity.

The inverse secondary SIE k_3^D/k_3^H in terms of the fractionation factors[40,42,43] is equal to 1 for $\chi = 0$ and 0.90 for $\chi = 1$. Therefore, if the maximum primary inverse SIE is reached at compound **4**, the decrease from compound **4** to **6** can be ascribed to an increase of the C−N bond cleavage to a later transition state T_3. These conclusions are entirely consistent with the Brønsted plot in the range of pK_N 7.5−9.9. In this range of pK_N, the SIE reflects a virtual transition state that changes from a partial hydron transfer to N to a partial C−N bond cleavage.

The new increase of SIE for compound **9** (ethylDTC) represents a change of mechanism. Unfortunately, the fractionation factor for the dithiocarbamic S−L bond is

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not known so the estimation of the SIE at equilibrium is impossible.

Conclusions

It is proposed that the acid cleavage of alkyldithiocarbamates occurs through two mechanisms, depending on the pK_N of the parent amine. At $pK_N < 10.5$ they decompose through a zwitterionic intermediate whose N-protonation is slower than the C−N bond breakdown when $pK_N < 9.2$. At $pK_N > 9.2$ the C−N bond breakdown is the slowest step.

The thiocarbonyl group is a powerful electron sink that decreases the basicity of the nitrogen of the parent amine by 14.1 pK units.

For parent amines with pK_N higher than ca. 10, a new mechanism emerges that is proposed to occur by an S to N intramolecular proton transfer of the dithiocarbamic acid, concerted with the breaking of the C−N bond.

Supporting Information Available: Kinetics analysis to obtain eq 7 (5 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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