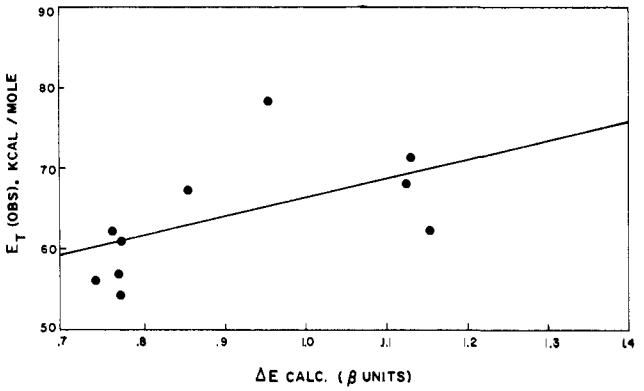


Figure 4. ω-Treatment correlation of experimental (E_T obsd.) and calculated (ΔE calcd.) transition energies. The calculated values are in units of β.

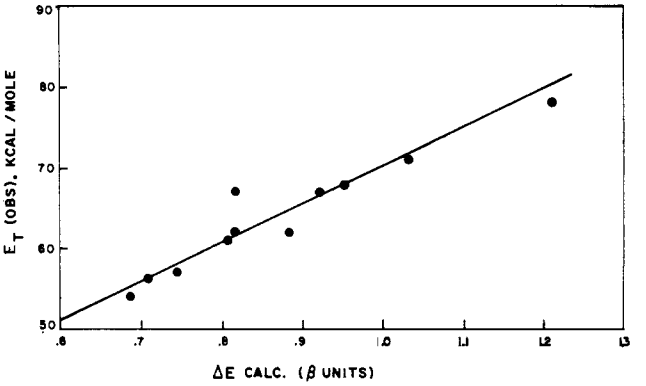


Figure 5. Perturbation treatment correlation of experimental (E_T obsd.) and calculated (ΔE calcd.) transition energies. The calculated values are in units of β.

plots give correlative evaluations of the resonance integral β; that of the perturbation correlation, 47.6 kcal./mole, is in the region frequently encountered for "spectroscopic" β-values,[3] while the value from the ω-treatment, 23.2 kcal./mole, is not.

The results are of a familiar (and, by now, no longer disconcerting) type. In theoretical treatments using one-electron wave functions, there is no readily predictable relationship between the degree of theoretical sophistication or refinement of the calculations and their success in correlating experimental data.

Mass Spectrometry in Structural and Stereochemical Problems. LXX.[1] A Study of the Fragmentation Processes of Some Five-Membered N-Alkyllactams and N-Alkylsuccinimides[2]

A. M. Duffield,[3] H. Budzikiewicz, and Carl Djerassi

Contribution from the Department of Chemistry of Stanford University, Stanford California. *Received February 20, 1965*

Deuterium labeling has enabled mechanistic interpretations to be presented for the principal ions formed in the mass spectrometric fragmentation of N-alkyl-2-pyrrolidones and N-alkylsuccinimides (alkyl = n-propyl or n-butyl). The most abundant ion in the mass spectrum of both N-alkylsuccinimides involves a double hydrogen transfer from the alkyl chain, and the sites from which these transfers originate in this and other rearrangement ions were demonstrated by deuterium labeling. High-resolution mass spectrometry established the composition of many of the peaks in the low-resolution spectra of the compounds studied.

Recently we described the mass spectrometric fragmentation behavior of some five- and six-membered lactams and their N-methylated derivatives[4] and, as an extension of this study, we now wish to report the processes occurring subsequent to electron impact in N-*n*-propyl- and N-*n*-butyl-2-pyrrolidone. These compounds were chosen in order to determine the effect of an N-alkyl chain on the fragmentation behavior particularly with regard to possible hydrogen transfer from the alkyl chain. As will be demonstrated below, rearrangement ions were observed and the sites of hydrogen transfer from the alkyl chains were elucidated by deuterium labeling experiments.

It was of interest to study the effect of a second carbonyl group adjacent to nitrogen in these substituted 2-pyrrolidones, and the mass spectra of N-*n*-propyl- and N-*n*-butylsuccinimide were determined especially since imides have as yet not been subjected to mass spectral scrutiny. Whereas the base peak in the spectra of the five-membered lactams studied arose from simple α-cleavage to nitrogen (see below), in the N-alkylated succinimides the most abundant peak had its genesis from loss of the alkyl chain less two hydrogen atoms. Consequently deuterium labeling of the side chain was commenced to establish the sites from which hydrogen was transferred.

Convenient synthetic procedures have been described for the preparation of alkyl bromides labeled with

(1) Paper LXIX: F. Komitsky, Jr., J. E. Gurst, and C. Djerassi, *J. Am. Chem. Soc.*, **87**, 1398 (1965).

(2) We are indebted to the National Institutes of Health of the U. S. Public Health Service (Grants No. GM-11309 and AM-04257) for financial support. The purchase of the Atlas CH-4 mass spectrometer was made possible through Grant No. NsG 81-60 from the National Aeronautics and Space Administration.

(3) Postdoctoral Research Fellow 1963–1965.

(4) A. M. Duffield, H. Budzikiewicz, and C. Djerassi, *J. Am. Chem. Soc.*, **86**, 5536 (1964).

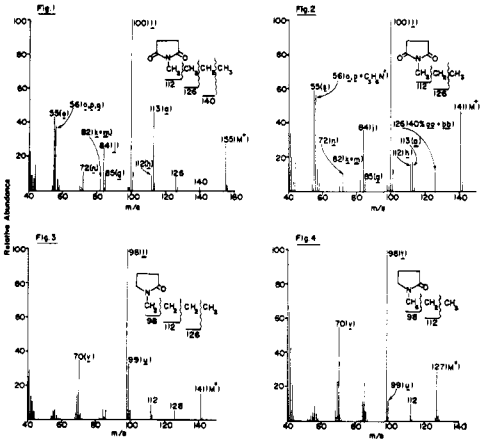


Figure 1. Mass spectrum of N-*n*-butylsuccinimide.
Figure 2. Mass spectrum of N-*n*-propylsuccinimide.
Figure 3. Mass spectrum of N-*n*-butyl-2-pyrrolidone.
Figure 4. Mass spectrum of N-*n*-propyl-2-pyrrolidone.

deuterium in specific positions,[5,6] and condensation of these labeled compounds with the anions of either 2-pyrrolidone or succinimide afforded the corresponding N-alkyl compounds deuterated in designated positions of the alkyl chain.

As the mass spectra of the N-alkylated succinimides contain more ions of mechanistic interest than do the corresponding 2-pyrrolidones their geneses are discussed first.

N-n-Butyl- and N-n-Propylsuccinimides (Figures 1 and 2). The mass spectra of N-*n*-butyl- and N-*n*-propylsuccinimides are, as might be predicted, very similar and the genesis of ions at any mass number need only be described for the butyl homolog except where deuterium labeling established different modes of origin. The mass shifts observed in the spectra of these compounds upon the introduction of deuterium into specific positions of the butyl and propyl chains are tabulated in Tables I and II, while Table III contains the results from high-resolution mass spectrometry[7] for the peaks of N-*n*-butylsuccinimide discussed in the text.

N-*n*-Butylsuccinimide exhibits a relatively intense molecular ion which is probably best represented by Ia and Ib. Less abundant peaks at *m/e* 112, 126, and 140 were shown by deuterium labeling (Table I) to correspond to α-, β-, and γ-cleavage of the alkyl chain.

A surprising exception to this result occurred with the ion of mass 126 (M − 15) in N-*n*-propylsuccinimide. In this instance 60% of the peak does have its genesis in the β-cleavage to nitrogen of the alkyl chain and loss of a methyl radical (Table II), but the remaining ion yield arises from loss of the α-carbon of the alkyl chain with its attached hydrogen atoms plus one hydrogen from the β-carbon (Table II). The simplest

(5) For a review of the currently available methods for the introduction of deuterium into organic molecules, see H. Budzikiewicz, C. Djerassi, and D. H. Williams, "Structure Elucidation of Natural Products by Mass Spectrometry," Vol. I, Holden-Day, Inc., San Francisco, Calif., 1964, Chapter 2.

(6) A. M. Duffield, R. Beugelmans, H. Budzikiewicz, D. A. Lightner, D. H. Williams, and C. Djerassi, *J. Am. Chem. Soc.*, **87**, 805 (1965).

(7) The high-resolution mass spectral data were determined in this laboratory by Dr. L. Dolejs on an A.E.I. MS-9 double focussing mass spectrometer.

Table I.[a] Principal Mass Spectral Peaks of N-*n*-Butylsuccinimide and Deuterated Analogs

Compd.[b]	Isotopic purity	*m/e* M+	M − 15	M − 29	M − 42	M − 43	M − 55	M − 70	M − 71	M − 73	M − 83	M − 99	M − 100
$RCH_2CH_2CH_2CH_3$		155	140	126	113	112	100	85	84	82	72	56	55
$RCD_2CH_2CH_2CH_3$	97% d_2	157	142 (q)	128 (q)	115 (q)	114 (q)	100 (85%) 101 (15%)	87 (q)	86 (q)	82 (q)	72 (q)	56 (56%) 58 (44%)	55 (q)
$RCH_2CD_2CH_2CH_3$	97% d_2	157	142 (q)	128 (q)	113 (q)	112 (q)	100 (22%) 101 (78%)	85 (80%)	84 (90%)	82 (60%) 83 (40%)	73 (90%)	56 (~70%) 57 (~15%) 58 (~15%)	55 (90%)
$RCH_2CH_2CD_2CH_3$	95% d_2	157	142 (q)	126 (q)	113 (10%) 114 (90%)	112 (q)	100 (16%) 101 (84%)	86 (80%)	84 (85%)	82 (60%) 83 (40%)	73 (80%)	56 (~85%) 58 (~15%)	55 (90%)
$RCH_2CH_2CH_2CD_3$	97% d_3	158	140 (q)	126 (q)	113 (q)	112 (q)	100 (85%) 101 (15%)	85 (q)	84 (q)	82 (q)	72 (q)	56 (~85%) 59 (~15%)	55 (90%)

[a] Tables I, II, and IV indicate the per cent shift of the compounds discussed when specifically labeled with deuterium. The symbol (q) refers to a quantitative transfer (*i.e.*, >95%) while the quoted values for per cent shifts are considered accurate to ±5% for peaks over 20% relative abundance. Occasionally approximate values may appear in the tables when no accurate determination was possible. [b] R= 

Table II.[a] Principal Mass Spectral Peaks of N-*n*-Propylsuccinimide and Deuterated Analogs

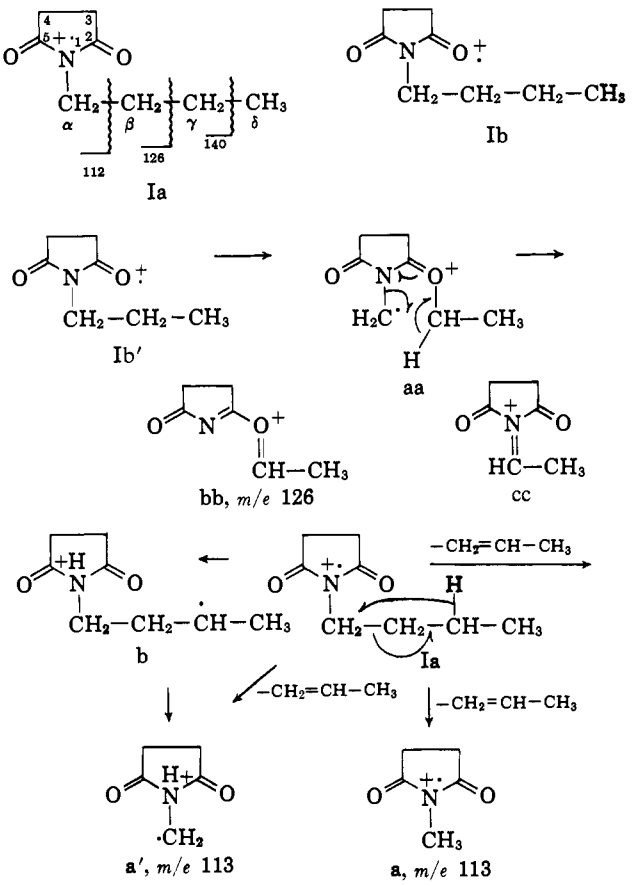
Compd.	Isotopic purity	M+	M − 15	M − 28	M − 29	M − 41	M − 56	M − 57	M − 59	M − 69	M − 85	M − 86
						m/e						
$RCH_2CH_2CH_3$	...	141	126	113	112	100	85	84	82	72	56	55
$RCD_2CH_2CH_3$	97% d_2	143	126 (40%) 128 (60%)	115 (q)	114 (q)	100 (70%) 101 (30%)	87 (q)	86 (q)	82 (80%) 83 (20%)	72 (90%)	56 (~45%) 58 (~55%)	55 (q)
$RCH_2CD_2CH_3$	95% d_2	143	127 (50%) 128 (50%)	113 (q)	112 (q)	100 (18%) 101 (82%)	85 (70%) 86 (30%)	84 (q)	82 (50%) 83 (50%)	73 (q)	56 (~90%) 57 (~10%)	55 (q)
$RCH_2CH_2CD_3$	75% d_3[b] 25% d_0	144	126 (60%) 129 (40%)	113 (15%) 114 (85%)	112 (q)	100 (15%) 101 (85%)	85 (70%) 86 (30%)	84 (q)	82 (45%) 83 (55%)	73 (90%)	56 (~90%) 58 (~5%) 59 (~5%)	55(q)

[a] See footnotes in Table I. [b] All peak shifts in the adjacent columns have been corrected for the presence of this d_0 contaminant.

Table III. High-Resolution[a] Mass Spectral Data of Some Ions of N-*n*-Butylsuccinimide[7]

Spectral Data			
Found	Calcd.	Composition	%
41.03931	41.03912	C_3H_5	80
41.02655	41.02643	C_2H_3N	20
42.04688	42.04695	C_3H_6	50
42.03440	42.03437	C_2H_4N	20
42.01060	42.01056	C_2H_2O	30
43.05511	43.05477	C_3H_7	80
43.00591	43.00581	CHNO	20
44.05007	44.05002	C_2H_6N	25
44.02639	44.02621	C_2H_4O	25
44.01390	44.01364	CH_2NO	50
55.05587	55.05477	C_4H_7	10
55.02063	55.01839	C_3H_2O	90
56.06264	56.06260	C_4C_8	17
56.02605	56.02621	C_3H_4O	50
56.01433	56.01364	C_2H_2NO	33
72.08019	72.08132	$C_4H_{10}N$	16
72.04537	72.04494	C_3H_6NO	84
82.02871	82.02929	C_4H_4NO	80
82.00493	82.00549	$C_4H_2O_2$	20
84.04499	84.04494	C_4H_6NO	100
85.05322	85.05276	C_4H_7NO	100
100.03844	100.03985	$C_4H_6NO_2$	100
112.03963	112.03985	$C_5H_6NO_2$	100

[a] Apparent resolution 1 in 15,000.



explanation would involve transfer of an ethyl radical in the molecular ion Ib′ to the charged heterocycle (aa) followed by back transfer of the β-hydrogen atom and formation of bb (*m/e* 126). However, it is also possible that the minor portion of the M − 15 peak corresponds to cc arising from a molecular ion with the charge on nitrogen. There is no obvious reason why this process (Ib′ → aa → bb) does not occur in N-*n*-butylsuccinimide or in N-*n*-butyl-2-pyrrolidone.

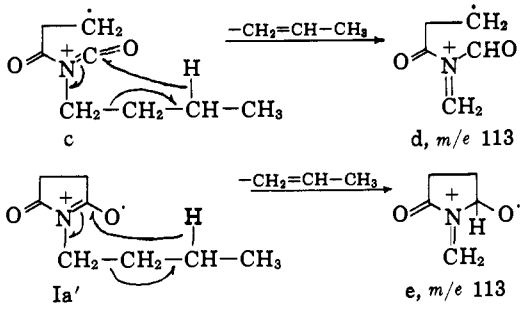
The peak present at *m/e* 113 in the spectrum of N-*n*-butylsuccinimide was completely displaced to *m/e* 115 in the α,α-dideuterated analog and therefore must encompass the α-carbon of the alkyl chain. High-resolution mass spectrometry[7] showed this ion to have the composition $C_5H_7NO_2^+$. Furthermore 90% of the hydrogen transferred in the genesis of this fragment originates from the γ-carbon atom of the alkyl chain (Table I). A mechanism consistent with this result is transfer of hydrogen in Ia to the α-carbon of the alkyl chain with synchronous α,β-bond rupture and generation of a (*m/e* 113). A similar four-numbered transition state has been proposed[8] for the expulsion of propylene from 1-phenylbutane.

An alternate possibility—that transfer of hydrogen from the γ-carbon of the alkyl chain occurs *via* a five-membered transition state to nitrogen with synchronous expulsion of propene and formation of a′ (*m/e* 113)—is equally probable although the stepwise formation of a′ proceeding *via* b is energetically less attractive in view of the conversion of a resonance-stabilized radical (Ia) into a secondary radical b.

Two other representations are possible for the origin of the ion of mass 113 in N-*n*-butylsuccinimide in which the γ-hydrogen atom of the side chain is transferred *via* a McLafferty rearrangement[9] to the carbon atom adjacent to nitrogen in either the product of α-cleavage (c) of the molecular ion (Ia) or in the resonance form (Ia′) of Ia. No distinction can be drawn between the possible representations a, a′, d, or e for the fragment of mass 113.

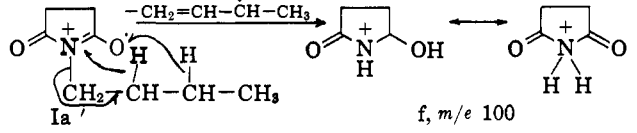
(8) J. D. McCollum and S. Meyerson, *J. Am. Chem. Soc.*, **81**, 4116 (1959).

(9) F. W. McLafferty, *Anal. Chem.*, **31**, 82 (1959). See also G. Spiteller and M. Spiteller-Friedmann, *Monatsh.*, **95**, 257 (1964); C. Djerassi, *Pure Appl. Chem.*, **9**, 159 (1964).

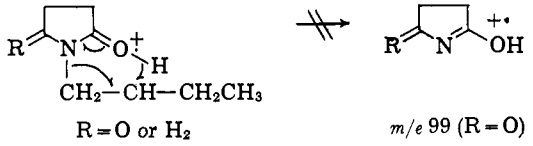


The base peak in the spectrum of N-*n*-butylsuccinimide (Figure 1) occurs at *m/e* 100 (M − 55) and high-resolution mass spectrometry[7] established its homogeneity and composition as $C_4H_6NO_2^+$ (Table III). This ion corresponds to the loss of the alkyl chain with transfer therefrom of two hydrogen atoms to the charged entity. Deuterium labeling (Table I) showed the source of the transferred hydrogen to be principally from the β- and γ-carbons of the alkyl chain. Intramolecular abstraction of a hydrogen atom from the γ-carbon of the side chain by oxygen in the resonance form (Ia′) of the molecular ion (Ia) and concomitant hydrogen transfer from the β-carbon atom to nitrogen with synchronous nitrogen–α-carbon bond rupture would yield the even-electron species f (*m/e* 100) as the charged fragment while the eliminated neutral component would be an allylic radical.

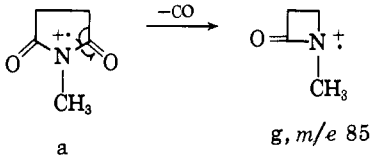
High-resolution mass spectrometry[7] indicated that the peak at *m/e* 100 in N-*n*-propylsuccinimide consisted of the ion $C_4H_6NO_2^+$ (95%), to which structure f can again be assigned (see also Table II), contaminated with the species $C_5H_{10}NO^+$ (5%). This process appears analogous to the double hydrogen rearrangement noted in higher esters of fatty acids.[10]



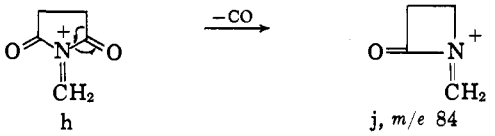
It is pertinent to note that just as in higher esters[10] of fatty acids the McLafferty rearrangement[9] is an unimportant process in the fragmentation of N-alkylsuccinimides and N-alkylpyrrolidones, as is evidenced by the weak abundance of the peaks at *m/e* 99 in the spectra of these compounds (Figures 1 and 2).



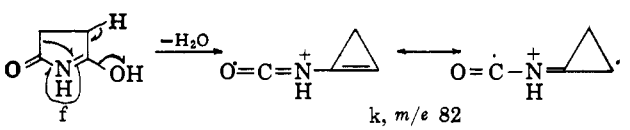
The ion of low yield of mass 85 (M − 70) in the spectrum of N-*n*-butylsuccinimide (Figure 1) was completely displaced to *m/e* 87 in the α,α-d_2 analog, while a transfer of 80% to *m/e* 86 was observed (Table I) in the γ,γ-dideuterated compound. These results require the retention of the α-carbon atom of the side chain in the charged species and indicate the source of the transferred hydrogen to be the γ-carbon of the butyl chain. Recognition of a metastable ion at *m/e* 64.1 ($85^2/113 = 63.9$) is consistent with the formation of at least a portion of this ion by the expulsion of 28 mass units (carbon monoxide or ethylene) from a (*m/e* 113). High-resolution mass spectrometry[7] (Table III) clearly demonstrates that only carbon monoxide is expelled as the neutral entity and the path a → g (*m/e* 85) is in agreement with these results. The loss of carbon monoxide from the fragment of mass 113 can equally well be visualized from the species a′ or e while a rearrangement process would be involved from fragment d.



The fragment of mass 84 (M − 71) in the spectrum of N-*n*-butylsuccinimide (Figure 1) was mainly unaffected in the deuterated analogs labeled on the β-, γ-, or δ-carbon atoms of the alkyl chain but was quantitatively transferred to *m/e* 86 in the α,α-dideuterio compound (Table I). This result, coupled with the recognition of a metastable ion at *m/e* 63.0 ($84^2/112 = 63.0$), is in harmony with the formation of this fragment by loss of 28 mass units (carbon monoxide or ethylene) from h (*m/e* 112), the ion formed by α-cleavage to nitrogen of the alkyl chain in Ia. The results from high-resolution mass spectrometry[7] (Table III) are only compatible with the expulsion of carbon monoxide (a result which leads to representation j (*m/e* 84) for the charged species).



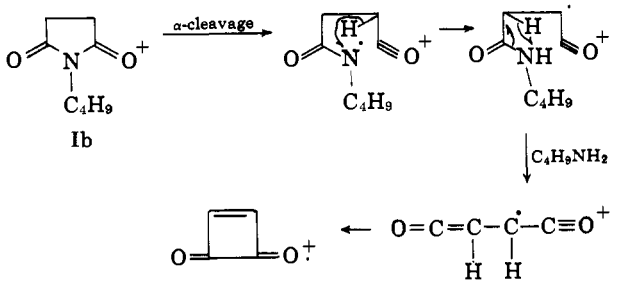
A peak of low abundance at *m/e* 82 (M − 73) in the spectrum of N-*n*-butylsuccinimide (Figure 1) was moved to the extent of 40% to *m/e* 83 in both the β,β- and γ,γ-dideuterated analogs (Table I). The occurrence of a metastable ion at *m/e* 67.2 ($82^2/100 = 67.2$) is consistent with at least a portion of this fragment having its genesis in the elimination of water from f (*m/e* 100), which in turn owes its origin to transfer of hydrogen from the β- and γ-positions. High-resolution mass measurements[7] (Table III) were consistent (75% $C_4H_4NO^+$ *vs.* 25% $C_4H_2O_2^+$) with the assumption that "dehydration" had occurred, and since this is hardly feasible in an intact pyrrolidone ring we propose that ring fission accompanies the fragmentation. A possible representation may be f → k (*m/e* 82).



The minor fragment (25% according to Table III) corresponding to $C_4H_2O_2^+$ at mass 82 in the spectrum of N-*n*-butylsuccinimide (Figure 1) can be represented by m (*m/e* 82) and could have its genesis in the expulsion of a molecule of *n*-butylamine from the molecular ion (Ib). Each step in the following sequence (which may well proceed in a concerted fashion)

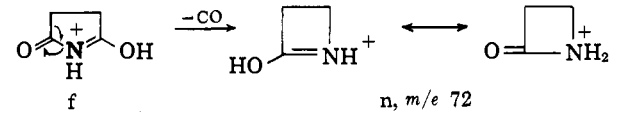
(10) R. Ryhage and E. Stenhagen, *Arkiv Kemi*, **14**, 483 (1959); F. W. McLafferty and M. C. Hamming, *Chem. Ind.* (London), 1366 (1958); F. W. McLafferty and R. S. Gohlke, *Anal. Chem.*, **31**, 2076 (1959).

has ample precedent in mass spectrometry, and only two of the many valence tautomers of m (*m/e* 82) are depicted. High-resolution mass spectrometry[7] established the composition of the peak at *m/e* 82 in N-*n*-

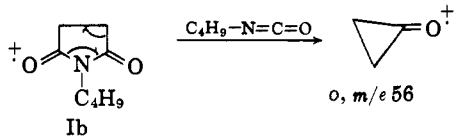


propylsuccinimide to be $C_3H_4NO^+$ (88%) and $C_4H_2O_2^+$ (12%), a ratio slightly different from that found in the butyl homolog.

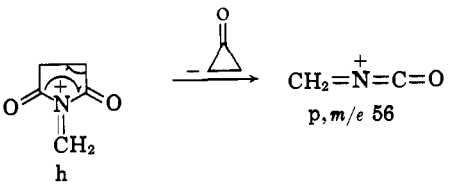
A peak of low intensity at *m/e* 72 (M − 83) in the mass spectrum of N-*n*-butylsuccinimide (Figure 1) was displaced to the extent of 90 and 80% to *m/e* 73 in the β,β- and γ,γ-dideuterated compounds, respectively. A relationship between the ions of mass 100 and 72 was established by recognition of a metastable ion at *m/e* 52.0 ($72^2/100 = 51.8$). The difference of 28 mass units was shown from high-resolution mass spectrometry[7] (Table III) to correspond to the expulsion of carbon monoxide such that the ion at *m/e* 72 can be assigned structure n.



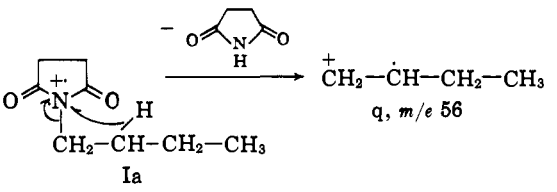
The spectrum (Figure 1) of N-*n*-butylsuccinimide contains an abundant ion at mass 56 (M − 99) which was affected principally (44% transfer to *m/e* 58) by deuterium labeling on the α-carbon atom of the alkyl chain. Shifts of approximately 15% to *m/e* 58 were recorded in the β,β- and γ,γ-dideuterated compounds and 15% to *m/e* 59 in the terminally trideuterated analog (Table I). These transfers were impossible to record with accuracy due to their small magnitude and to the occurrence of peaks of low abundance at *m/e* 57 and 58. High-resolution mass spectrometry[7] (Table III) established the composition of *m/e* 56 as $C_3H_4O^+$ (50%), $C_2H_2NO^+$ (33%), and $C_4H_8^+$ (17%). The first of these ions corresponds to ionized cyclopropanone (o), which could have its genesis from the molecular ion (Ib).



Since the fragment corresponding to o would be unaffected in those derivatives deuterated in the alkyl chain it follows from the labeling results (Table I) that the other two ions of mass 56 must incorporate the α-carbon atom of the alkyl chain. A mechanism consistent with these facts for the $C_2H_2NO^+$ ion is depicted in h → p (*m/e* 56), the expelled neutral entity in this instance being cyclopropanone.



The elemental composition ($C_4H_8^+$) of the remaining ion which contributes to the *m/e* 56 peak virtually requires that it encompasses the side chain less one hydrogen atom. Deuterium labeling (Table I) showed that the transferred hydrogen atom originated from the β-carbon atom of the side chain (*m/e* 56 transferred to *m/e* 57 in approximately 15% yield). One may conclude, therefore, that heterolysis of the nitrogen–α-carbon bond in Ia would yield succinimide as the neutral entity and ionized butene q as the charged species. The driving force for this fragmentation evidently is the expulsion of the stable neutral succinimide molecule.



The composition of the peak at *m/e* 56 in the spectrum of N-*n*-propylsuccinimide (Figure 2) should differ from that determined for the butyl homolog in view of the absence of the species q. High-resolution mass spectrometry[7] showed the composition of this peak in the propyl homolog to be $C_2H_2NO^+$ (45%, p), $C_3H_4O^+$ (45%, o), and $C_3H_6N^+$ (10%). The first two of these fragments probably arise in the same manner as described for the ions p and o in the butyl homolog. The remaining fragment, $C_3H_6N^+$, corresponds to the nitrogen atom together with the propyl side chain less one hydrogen atom, and deuterium labeling (5% transfer) established a source (50%) of the eliminated hydrogen as the γ-carbon atom of the propyl chain (Table II).

The ion yield at *m/e* 55 (M − 100) in the spectrum of N-*n*-butylsuccinimide (Figure 1) was almost unaffected in all positions of the alkyl chain, while high-resolution mass spectrometry[7] (Table III) established the composition as $C_3H_3O^+$ (90%) and $C_4H_7^+$ (10%). The genesis of the principal fragment of mass 55 can be envisaged as proceeding through α-cleavage of the molecular ion (Ia) to yield r, which on hydrogen migration to nitrogen and heterolysis of the N–C-5 bond would yield the even-electron species s (*m/e* 55). In the mass spectrum (Figure 2) of the propyl homolog *m/e* 55 was shown from high-resolution mass spectrometry[7] to consist only of the species $C_3H_3O^+$, which can also be assigned structure s.

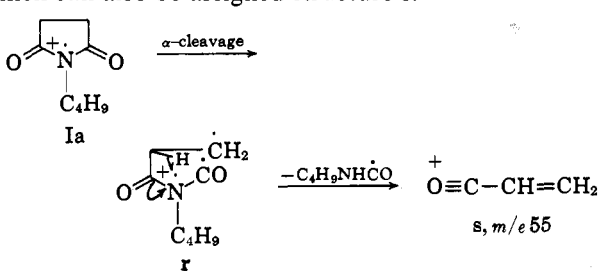


Table IV.[a] Principal Peaks in the Mass Spectra of N-*n*-Butyl-2-pyrrolidone and Deuterated Analogs

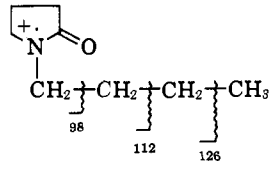
Compd.[b]	Isotopic purity	M+	M − 15	M − 29	M − 42	M − 43	M − 71
$RCH_2CH_2CH_2CH_3$	...	141	126	112	99	98	70
$RCD_2CH_2CH_2CH_3$	97% d_2	143	128 (q)	114 (q)	101 (q)	100 (q)	72 (q)
$RCH_2CD_2CH_2CH_3$	97% d_2	143	128 (q)	114 (q)	99 (q)	98 (q)	70 (q)
$RCH_2CH_2CD_2CH_3$	95% d_2	143	128 (q)	112 (q)	99 (10%) 100 (90%)	98 (q)	70 (q)

[a] See footnote to Table I. [b] R= 

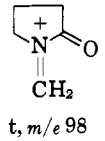
It is difficult to rationalize the genesis of the ions in the mass range *m/e* 41 to *m/e* 44 in the spectrum of N-*n*-butylsuccinimide from the results of deuterium labeling, as only small displacements occurred in the deuterated analogs. High-resolution mass spectrometry[7] established the composition tabulated in Table III for these fragments.

N-n-Butyl- and N-n-Propyl-2-pyrrolidone (Figures 3 and 4). The mass spectra of N-*n*-butyl- and N-*n*-propyl-2-pyrrolidone (Figures 3 and 4) are very similar, both containing few abundant ions and the base peak in both instances occurring at *m/e* 98. In view of the similarities between the two spectra deuterium labeling was performed only with the butyl homolog.

The peak at *m/e* 98 dominates the spectrum of N-*n*-butyl-2-pyrrolidone and in the derivatives deuterated on the alkyl chain only the compound labeled with deuterium on the α-carbon (transferred to *m/e* 100) caused a shift to higher mass (Table IV). This result is consistent with this ion's genesis by α-cleavage of the alkyl chain to nitrogen in the molecular ion II and formulation as t (*m/e* 98).



II

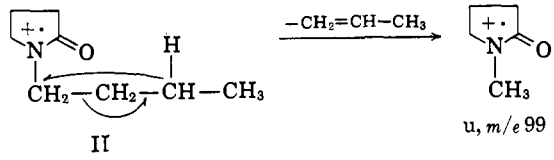


t, *m/e* 98

Ions of low abundance at *m/e* 126 and *m/e* 112 in the spectrum of N-*n*-butyl-2-pyrrolidone (Figure 3) correspond to β- and γ-cleavage of the alkyl chain (Table IV) and require no additional comment.

The only rearrangement ion of any abundance in the spectrum of N-*n*-butyl-2-pyrrolidone (Figure 3) occurs at *m/e* 99 (M − 42). Deuterium labeling established that 90% of the hydrogen transferred in its formation came from the γ-carbon of the alkyl chain (Table IV). This ion thus has its origin in a process similar to that of ion a (*m/e* 113) in the spectra (Figures 1 and 2) of N-*n*-butyl- and N-*n*-propylsuccinimide.

Four possible modes of formation exist for the ion at *m/e* 99 dependent on the site to which hydrogen is transferred. One of these representations (u) is shown but others, analogous to the ions a′, d, or e in the case of the alkylsuccinimides, cannot be excluded.

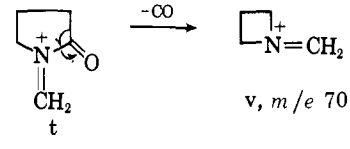


II

u, *m/e* 99

α-Cleavage adjacent to nitrogen in the N-alkylsuccinimides studied resulted in the formation of the ion h (*m/e* 112) of low abundance, while in the corresponding 2-pyrrolidones this process generated the base peak. However the base peak in the spectra of the alkylsuccinimides resulted from loss of the alkyl chain minus two hydrogen atoms. Such a process, if applicable to the N-*n*-alkyl-2-pyrrolidones investigated, would generate an ion of mass 86. Both N-*n*-butyl- and N-*n*-propyl-2-pyrrolidone (Figures 3 and 4) contain peaks of low abundance at *m/e* 86 (6 and 7% of the base peak). The difference in the modes of fragmentation of the molecular ions of the alkyl succinimides and alkyl-2-pyrrolidones studied might be attributed to the larger number of atoms involved in resonance forms of the molecular ions in the former compounds.

An ion of appreciable abundance at *m/e* 70 (M − 71) in the spectrum of the N-*n*-butyllactam was quantitatively transferred to *m/e* 72 in the α,α-dideuterio analog and was unaffected (see Table IV) in those derivatives deuterated on the β- or γ-carbon atoms of the alkyl chain. Deuterium labeling thus implicated the α-carbon atom of the alkyl chain with the charged species, while a metastable ion at *m/e* 50.2 ($70^2/98$ = 50.0) indicated that at least a portion of this ion owed its formation to the loss of 28 mass units from species t (*m/e* 98). High-resolution mass spectrometry[7] established the composition of this fragment as $C_4H_8N^+$, which is consistent with the expulsion of carbon monoxide from t with formation of the species v (*m/e* 70). This process is completely analogous to the production of j from h in the succinimides.

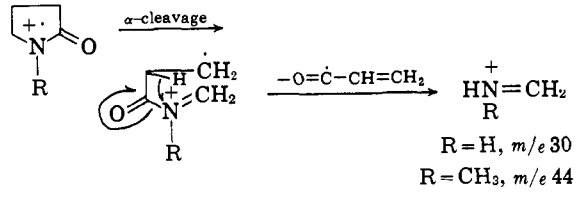


t

v, *m/e* 70

The remaining ions in the range *m/e* 41 to *m/e* 44 were hardly affected by deuteration of the alkyl chain and little can be said about their modes of formation except that they arise principally from fragmentation of the lactam ring.

The base peak in the spectra of both 2-pyrrolidone and N-methyl-2-pyrrolidone occurs at *m/e* 30 and *m/e* 44, respectively, and is generated according to the following mechanism.[4]



R=H, *m/e* 30

R=CH₃, *m/e* 44

It is interesting to note that this particular mode of fragmentation is almost completely lacking in the spectra of the higher N-alkyl-2-pyrrolidones as shown by the low intensity of the ions at *m/e* 86 (Figures 3 and 4).

Summary

Both N-alkylsuccinimides and N-alkyl-2-pyrrolidones studied (R = *n*-propyl and *n*-butyl) displayed α- and β-cleavage, and in the butyl homologs, γ-cleavage, of the alkyl chain. In N-*n*-propylsuccinimide loss of a methyl group occurred to the extent of 60% by β-cleavage. The remainder arises by expulsion of the α-carbon of the alkyl chain with its attached hydrogen atoms plus one hydrogen from the β-carbon atom and thus must involve an ethyl migration to the charged species (bb or cc).

A rearrangement ion at *m/e* 113 (a,a′, d, or e) in the spectra of the two alkyl succinimides studied has a similar genesis to the fragment of mass 99 (u) in the alkylated 2-pyrrolidones, *viz.*, transfer of the γ-hydrogen atom of the alkyl chain to the charged heterocycle with the elimination of a neutral olefin.

The most abundant ion formed in the mass spectrometric fragmentation of the two N-alkylated succinimides studied arises from transfer of two hydrogen atoms, principally from the β- and γ-carbon atoms of the alkyl chain, to the heterocyclic nucleus with fission of the nitrogen–α-carbon bond of the side chain and generation of f (*m/e* 100). In contrast, the base peak in the spectra of N-*n*-alkyl-2-pyrrolidones is formed from α-cleavage of the alkyl chain to nitrogen, yielding species o (*m/e* 98).

Loss of 28 mass units from the most abundant ions in the spectra of both N-alkylsuccinimides (*m/e* 100) and 2-pyrrolidones (*m/e* 98) is accomplished by elimination of carbon monoxide and generation of n and v, respectively, while no loss of ethylene is observed. This preferred loss of carbon monoxide over ethylene is manifest in the genesis of the ions g (*m/e* 85) and j (*m/e* 84) in the spectra of the N-alkylated succinimides.

The peak at *m/e* 56 in the spectrum of N-*n*-butylsuccinimide was shown to be a multiplet by high-resolution mass spectrometry and to consist of the species $C_3H_4O^+$ (50%), $C_2H_2NO^+$ (33%), and $C_4H_8^+$ (17%), while *m/e* 55 is virtually homogeneous ($C_3H_3O^+$) and arises by rupture of the succinimide ring.

Experimental[11]

1-Bromopropane-3,3,3-d_3. Acetic acid-d_4[13] (5 g.) in dry ether (30 ml.) was slowly added to a slurry of lithium aluminum hydride (4 g.) in dry ether (100 ml.). The reaction mixture was heated under reflux for 2 hr. when excess reagent was destroyed by the dropwise addition of water. The inorganic salts were dissolved in 25% sulfuric acid (100 ml.) and the aqueous phase was extracted continuously with ether during 20 hr. The combined ether extracts were dried ($MgSO_4$) and the ether was removed through a fractionating column. The residue after removal of the ether[14] was heated with 48% hydrobromic acid (20 ml.) containing concentrated sulfuric acid (5 ml.) and the liberated ethyl bromide was collected under water, separated, and dried (calcium chloride), yielding ethyl bromide (3 g.). The Grignard reagent, prepared from the labeled ethyl bromide (3 g.) and magnesium turnings (1 g.) in dry ether (20 ml.), was poured onto crushed Dry Ice (50 g.). After evaporation of excess Dry Ice, 10% hydrochloric acid (30 ml.) was added and the solution was extracted continuously with ether during 18 hr. The ether solution was dried (magnesium sulfate) and reduced with excess lithium aluminum hydride in ether solution. Bromination of the resulting propanol-3,3,3-d_3 (1 g.) afforded 1-bromopropane-3,3,3-d_3 (0.75 g.), which was homogeneous on vapor phase chromatography[6] and was shown by mass spectrometry to contain 75% d_3 and 25% d_0 species.

N-Alkylation of Succinimide. Succinimide (100 mg.) was heated under reflux with 0.5 ml. of a solution of sodium hydroxide (4 g.) in ethanol (50 ml.) until a homogeneous solution resulted (approximately 10 min.). The labeled alkyl bromide (100 mg.) was added and the reaction mixture was heated under reflux overnight. Solvent was removed on the steam bath and the residue was distilled, b.p. 110–120° (0.8 mm.), air bath temperature. The pure N-alkylated succinimide was isolated by preparative vapor phase chromatography.[11]

N-Alkylation of 2-Pyrrolidone. 2-Pyrrolidone (100 mg.) in anhydrous tetrahydrofuran (3 ml.) was stirred with sodium hydride (150 mg.) for 30 min. at room temperature. The labeled alkyl bromide (100 mg.) in anhydrous tetrahydrofuran (2 ml.) was added and stirring was continued overnight at room temperature and then the solution was heated under reflux for 1 hr. The reaction mixture was cooled, diluted with anhydrous ether, and filtered. The filtrate was concentrated on the steam bath and the N-alkylated 2-pyrrolidone was isolated by preparative vapor phase chromatography.[11]

(11) All mass spectra, other than high-resolution mass spectra[7] (see also Table III), were obtained with an Atlas CH-4 mass spectrometer using the AN4 Ion Source with the source and reservoir thermostated at 60°. The ionizing voltage was maintained at 70 e.v. and the ionizing current at 20 μa., using a tungsten ribbon filament. Preparative gas phase chromatography was carried out using a Wilkens Aerograph instrument and 20% polybutylene glycol as the stationary phase.[12] At a temperature of 190° and helium pressure of 8 p.s.i., N-*n*-propyl- and N-*n*-butylsuccinimide had retention times of 8 and 13 min., respectively. At an oven temperature of 185° and helium pressure of 6 p.s.i., N-*n*-propyl- and N-*n*-butyl-2-pyrrolidone had retention times of 6.5 and 9 min., respectively. Deuteriated alkyl bromides were prepared according to a published procedure.

(12) L. D. Quin, *J. Org. Chem.*, **24**, 911 (1959).

(13) Purchased from Cal Biochem of Los Angeles, Calif., and of 98% d_4 content.

(14) Failure to remove all the ether from the labeled ethanol resulted in the formation of ethyl bromide from cleavage of ethyl ether during the subsequent bromination step. This unlabeled ethyl bromide was responsible for the final propyl bromide having 25% d_0 species (determined by mass spectrometry).