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STEREOCHEMISTRY OF RETRO–DIELS–ALDER FRAGMENTATION IN GAS–PHASE IONS FORMED BY CHEMICAL IONIZATION

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Abstract—Retro Diels Alder fragmentation is highly stereospecific in the diones 1 under chemical ionization conditions, both with methane and isobutane as the reagent gases. Only the *cis*-isomers yield abundant protonated diene and quinone ions. The isotope effect indicates preferential protonation on a CO oxygen, and a subsequent H-migration prior to the formation of the protonated diene cations in the *cis* isomers.

Configuration has been shown to have a decisive effect on the fragmentation under electron impact in numerous systems.[1,2] The different decomposition of stereoisomers was used in some cases as a proof for fragmentation mechanisms as well as a tool for the determination of ion structures. Only few cases of an effect of configuration on the behavior of organic ions obtained by chemical ionization (CI) have been recorded.[3-9] Ground state distances between oxygen and active hydrogen atoms have been shown to have an effect on the abundance of ions formed by the loss of H_2O from several ketones under CI. Stereoisomers in which cyclic transition states for such eliminations are possible without rearrangement of the skeleton gave rise to more abundant $[M+H-H_2O]^+$ ions.[3] Another stereochemical effect is the stabilization of the MH^+ ions by proton bridging of two or more functional groups, resulting in more abundant MH^+ ions for stereoisomers in which such bridging is possible.[4,5]

In view of the meager information available on the structure of ions formed by chemical ionization[10,11] and on the mechanisms of their decomposition it was of interest to examine the extent of stereospecificity of more fragmentation processes these ions may undergo.

In previous publications we have shown that retro Diels–Alder (RDA) fragmentation is a highly stereoselective process in several systems under electron impact.[12-14] Thus, for example, only *cis*-isomers in system 1 undergo this fragmentation, yielding the most abundant ions in the mass spectra (Scheme 1).[12] In the mass spectra of the *trans*-isomers the retro Diels–Alder ions are practically absent, while the molecular ions become the most abundant species. It is obvious that in this and in other analogous systems[13-15] the RDA fragmentation under electron impact resembles the thermal retrodiene reaction, indicating similarity in mechanism of the two related processes.[16]

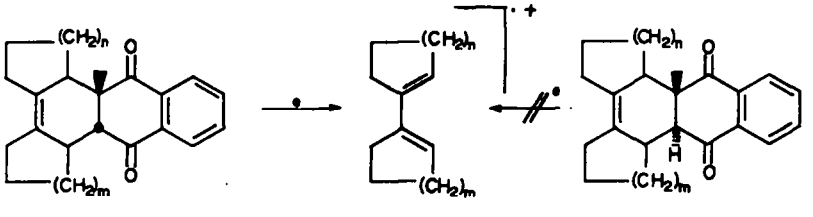
We decided to investigate these systems under chemical ionization conditions in order to determine whether they would undergo a RDA fragmentation, and if yes, whether this process would exhibit stereospecificity in analogy to the electron impact process.

RESULTS AND DISCUSSION

The CI mass spectra of diketones 1 show prominent differences between the stereoisomers (Table 1). In all cases the protonated *cis*-diones 1-*cis* undergo retro Diels–Alder fragmentation yielding abundant protonated dienes. These fragment ions are the most abundant ions when the CI reagent gas is methane. With isobutane as reagent the MH^+ ions are the most abundant ions (with the exceptiion of 1e-*cis*) but the protonated dienes are also highly abundant. These ions are not observed or are of very low abundance in the CI mass spectra of the *trans*-isomers 1-*trans*. In these compounds the MH^+ ions are the most abundant ions, both with methane and isobutane as CI reagents. The results show that the retro Diels–Alder fragmentation is highly stereospecific both in the radical molecular ions $M^{\cdot+}$ formed under electron impact and in the even-electron MH^+ ions obtained by chemical ionization.

An interesting difference between the electron impact and chemical ionization induced fragmentations is the formation of protonated quinones (ions *b*) by CI (Scheme 2).

These ions are also formed *only* from the *cis*-isomers 1-*cis*, indicating that they are products of a one-step



1—*cis* 1—*trans*

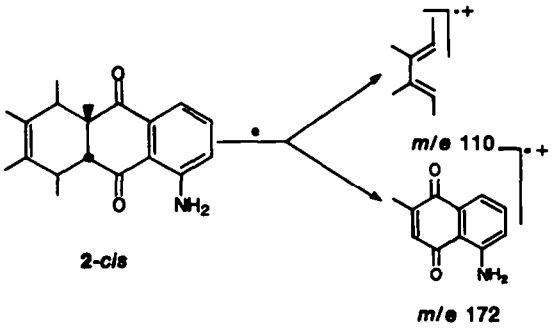
Scheme 1.

Table 1. The abundance of ions a and b in the CI mass spectra of stereoisomeric diones.

CI-reagent	Compound	Relative abundance, %		
		ion a	ion b	MH^+
Methane	1a-cis	100	27	22
	1a-trans	2	3	100
	1b-cis	100	19	92
	1b-trans	1	0	100
	1c-cis	100	29	37
	1c-trans	0	1	100
	1d-cis	100	11	83
	1d-trans	0	0	100
	1e-cis	100	51	31
Isobutane	1a-cis	96	2	100
	1a-trans	0	0	100
	1b-cis	19	20	100
	1b-trans	1	0	100
	1c-cis	57	45	100
	1c-trans	2	1	100
	1d-cis	28	24	100
	1d-trans	0	0	100
	1e-cis	100	28	20

fragmentation which has the characteristics of the RDA process. These ions are in most cases of lower abundance than the protonated dienes a (see Table 1).

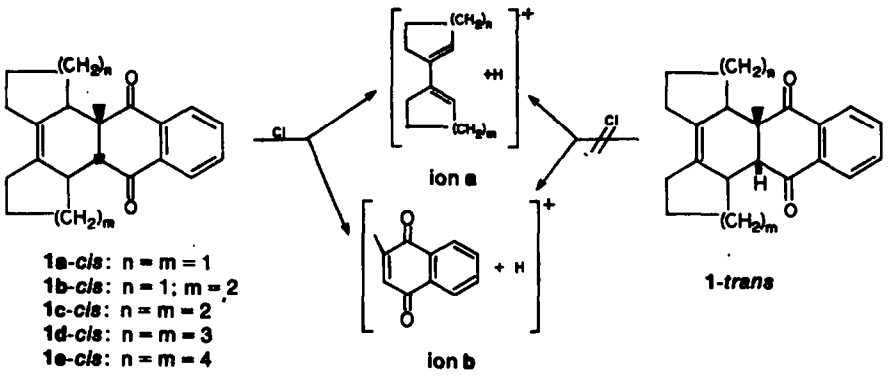
Quinone cations have not been generally detected as retro Diels–Alder fragments in the electron impact mass spectra of diketones.[12-14] Charge is retained in these cases in the diene fragments, because of their lower ionization potentials, in keeping with "Stevenson's rule".[17] One exception is the amino-diketone 2, which gives rise to both the diene and the quinone cations, because of the lower ionization potential of 5-amino-2-methylnaphthoquinone.[13]



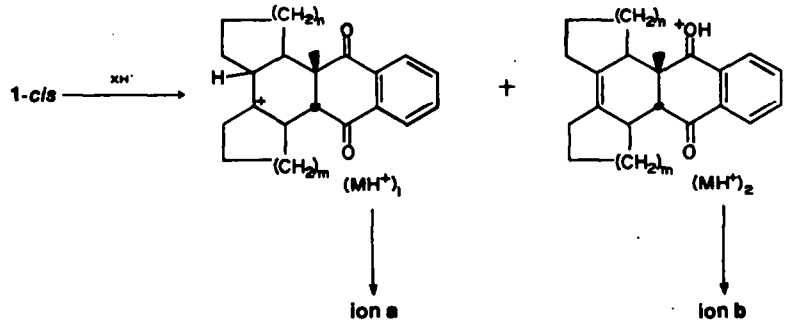
Two explanations can be suggested for the formation of both ions a and b under chemical ionization:

(i) They may result from MH^+ ions where the molecules M were initially protonated at different sites. For example, $(MH^+)_1$ protonated at the double bond could be the percursor of the protonated dienes a, while $(MH^+)_2$ protonated at a carbonyl group could lead to the formation of the protonated quinones b (Scheme 3).

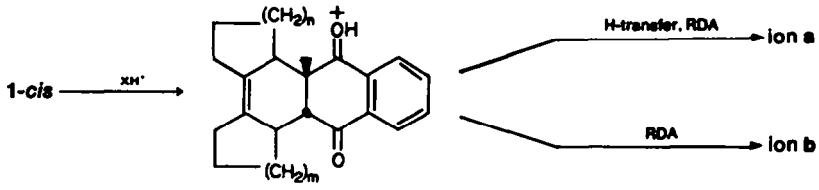
(ii) Both ions a and b may result from single type MH^+ ions, with the proton attached to the functional group of highest proton affinity (Scheme 4). If this is the case, proton transfer must be assumed as a step in the mechanism leading to the formation of one of the



Scheme 2.



Scheme 3.



Scheme 4.

products. If, for example, the initial protonation occurs at one of the carbonyl groups, ion a can be formed by a proton migration to the double bond accompanying the RDA fragmentation. It should be mentioned here that the distance between that hydrogen and the region of the double bond is not large and hydrogen migrations, although in the opposite direction, have been reported in similar systems under electron impact.[18-22]

The weak point in mechanism (i) is that the MH^+ ion protonated at the double bond $(MH^+)_I$ does not have the original double bond necessary for the RDA fragmentation. It has electron deficiency in that region, and would not be expected to give rise to a RDA fragmentation. A two-step fragmentation initiated by the cleavage of the bond next to the charged C-atom in $(MH^+)_I$ is excluded by the high stereospecificity of the process.

A support for pathway (ii) could be found in data obtained with CD_4 as reagent. The ratios of abundances of ions a/b measured from the CH_4- and CD_4-CI mass spectra are listed in Table 2. It is evident that these ratios are lower with CD_4 as reagent. This result can be easily explained by a primary isotope effect for mechanism (ii), in which hydrogen migration is accompanying the RDA reaction. For mechanism (i) one would have to assume a deuterium isotope effect on the ratio of abundances of the ions $(MH^+)_I/(MH^+)_2$, or a secondary isotope effect.

We measured the abundance ratios of the MH^+ (or MD^+) ions of a mixture of an olefin (cyclohexene) and a ketone (2-butanone) under chemical ionization with CH_4 and CD_4 as reagent gases and could not detect any isotope effect on this ratio within the experimental error. This result together with the unlikeliness of large secondary isotope effect seems to disfavor mechanism (i).

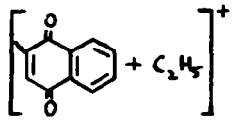
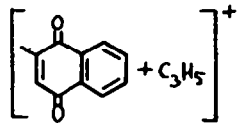
Table 2. Abundance ratios obtained with CH_4 and CD_4 as CI reagents.

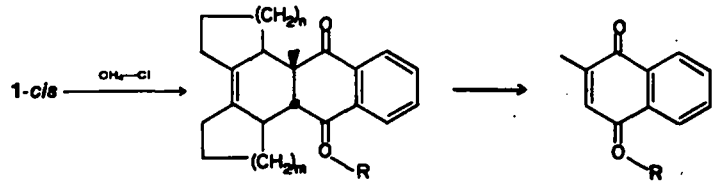
Compound	a/b (CH_4)	a'/b' (CD_4)*
1a-cis	3.3 ± 0.3	2.0 ± 0.4
1b-cis	5.2 ± 0.2	1.6 ± 0.1
1c-cis	3.0 ± 0.6	1.2 ± 0.3
1d-cis	8.4 ± 0.6	2.5 ± 0.1
1e-cis	1.8 ± 0.2	1.3 ± 0.1

* ions a' and b' are the deuteron analogs of ions a and b.

It is also of interest to note that [quinone $+C_2H_5]^+$ and [quinone $+C_3H_5]^+$ were detected in the CH_4- mass spectra of the *cis*-diketones 1-*cis*. These ions were shifted by 5 mass units when CD_4 was used as the reagent gas. The abundances of these ions are listed in Table 3. The absence of analogous [diene $+C_2H_5]^+$ and [diene $+C_3H_5]^+$ ions indicates that the attack by $C_2H_5^+$ and $C_3H_5^+$ ions of the molecules of 1-*cis* occurs only at the

Table 3. The relative abundances of adduct ions [%].

Compound \ Adduct ion		
1a-cis	17	3
1a-trans	3	0
1b-cis	13	4
1b-trans	0	0
1c-cis	19	4
1c-trans	3	0
1d-cis	14	3
1d-trans	0	0
1e-cis	22	4



Scheme 5.

quinone moiety, probably at one of the carbonyl groups. A transfer of a C_2H_5 or C_3H_5 group from oxygen to the double bond region is improbable in contrast to the hydrogen migration as in mechanism (ii) (Scheme 5).

CONCLUSION

The results presented show that retro Diels–Alder fragmentation takes place in the protonated gas-phase diones 1 with very high degree of stereospecificity, which is similar to that observed in the ground-state molecules and in the analogous radical cations obtained by electro impact. It is clear that no isomerization to a common structure occurs in the MH^+ ions of the *cis*- and *trans*-isomers prior to this process and it can be assumed that they retain their original, configuration.

Recently the site of protonation in MH^+ ions obtained by CI has been determined in simple aromatic systems using D_2O as the reagent gas.[11] The number of exchangeable H atoms was used as the criterion for the localization. This method is ineffective in cases where no exchange takes place. In this work the site of protonation was determined with the aid of an isotope effect, which could be detected because of the occurrence of competing fragmentations.

EXPERIMENTAL

The chemical ionization mass spectra were recorded with a DuPont 21-490B single focusing instrument equipped with the commercial dual CI/EI source. Reagent gases used were CH_4, CD_4 and isobutane.

Preparation of materials used in this study has been reported elsewhere.[12]

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