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PERICYCLIC AND HETEROELECTROCYCLIC MECHANISMS FOR THE CYCLIZATION OF 1,3,5-HEXATRIEN-1-ONE AND ITS 6-AZA ANALOG

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*The cyclization of 1,3,5-hexatrien-1-one, **1**, and the Z- and E-isomers of 1-aza-1,3-butadienylketene **3** were studied using the semiempirical AM1 and PM3 methods. Cyclizations of compounds **1** and Z-**3** are shown to occur via a mono-rotation mechanism with barriers of 15.49 and 32.85 kcal/mol respectively. The reactions proceed via non-planar transition states which result from rotation of the methylene group for compound **1** and the imino group for compound Z-**3**. Cyclization of E-**3** proceeds via a non-rotatory mechanism through a planar transition state. The activation barrier is 4.83 kcal/mol (AM1). The electronic structures of the initial and final states, and of some intermediate structures, including the transition states for the cyclization of compounds **1** and **3**, were analyzed by the natural orbital method using HF/6-31G*//AM1 calculations. Energetic, structural, and orbital criteria indicate the heteroelectric mechanism for the cyclization of compound E-**3** and the pericyclic mechanism for the cyclization of compounds **1** and Z-**3**.*

Keywords: 1H-pyridin-2-one, cyclohexa-1,3-dien-5-one, heteroelectrocyclization, quantum-chemical calculations, pericyclic reactions, 1,6-cyclizations.

Pericyclic reactions of heteroatom π-conjugated compounds provides a powerful arsenal of synthetic methods for a variety of heterocyclic compounds [1-7]. On the other hand these same heteroatomic compounds, including heterocycles, are unique models for the elucidation of new mechanisms of chemical reactions [8-16]. Successive replacement of terminal methylene groups in the molecules of π-conjugated compounds with one and two heteroatoms leads to the possibility of dirotatory, monorotatory, and nonrotatory mechanisms of cyclization [2-16]. We have recently [17,18] proposed a classification of electrocyclic reactions of heteroatomic compounds, in which the new σ-bond is formed as a result of the interaction of orthogonal π-systems of orbitals, as heteroelectrocyclic reactions. These occur with a low activation energy (energetic criteria), *via* planar transition states (structural criteria), with the formation of new σ-bonds as a result of the interaction of orthogonal π-systems of orbitals (orbital and decisive criteria). Birney [19-26] showed that this mechanism may also occur in other types of pericyclic reactions such as cycloadditions, sigmatropic hydrogen shifts, and cheletropic conversions. He proposed that these reactions should be classified as pseudopericyclic reactions.

Lone electron pairs (LEP) play an important role in the formation of a new σ-bond in heteroelectrocyclic reactions. In studying the cyclization of the *Z*- and *E*-isomers of 2-diazoethanimine we succeeded in carrying out a comparative study of heteroelectrocyclic and pericyclic mechanisms of cyclization

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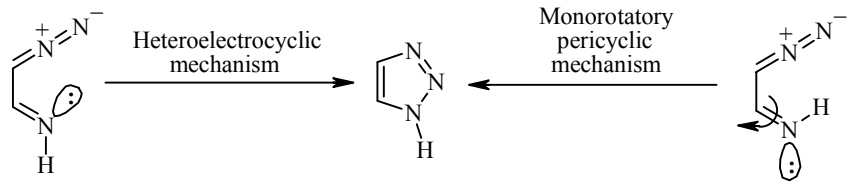
of practically the same molecule [12]. The preference of the heterocyclic mechanism for this reaction was demonstrated. The conversion of the LEP of the nitrogen atom of the imino group into the new N–N bond of the triazole ring was demonstrated using the NBO natural orbital (NO) method [12].

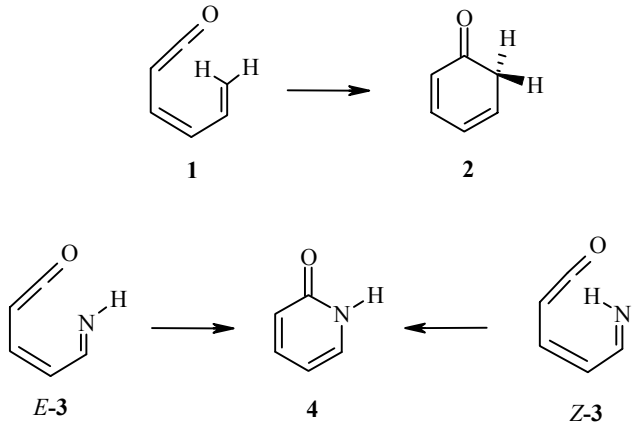


It should be noted that the natural orbital method is very convenient, since it permits the direct conversion of orbitals from reagents to reaction products and thus reveals the details of the reaction mechanism.

The present paper is a continuation and development of our approach to the investigation of the mechanism of the cyclization of the *Z*- and *E*-isomers of aldimines in which the C=N bond of the imino groups is involved in π-conjugated systems, and the theoretical study of the cyclization of 1,3,5-hexatrien-1-one (**1**) and the *Z*- and *E*-isomers of 5-imino-1,3-pentadien-1-one (**3**).

Similar types of cyclization are quite widely distributed in heterocyclic organic chemistry and are used to obtain mono-, bi-, and tricyclic heterocycles [5]. The photochemical opening of the ring of the products of cyclization of these products is the basis of an original method for the synthesis of macrocyclic heterocyclic compounds [5].

Ketenes **1** and **3** contain a conjugated π-system and an additional electrophilic π_x-bond, orthogonal to the plane of the π-system, between the terminal carbon atoms of the π-system and the oxygen atom. Consequently they are suitable models for carrying out theoretical studies of variations in the mechanism of cyclization of π-conjugated compounds on introduction of heteroatoms at the terminal position of π-systems and also for a comparative study of pericyclic and heteroelectrocyclic mechanisms of cyclization.



All calculations were carried out using the MOPAC 6.0 suite of programs [28] and Gaussian 94 [29]. In the first stage optimization of the geometric parameters of all the structures was carried using the semi-empirical PM3 [30, 31] and AM1 [32, 33] methods using the Broyden[34]–Fletcher[35]–Goldfarb[36]–Shanno[37] algorithm. Stationary points were characterized as maxima/minima (ground/transitions states) on the basis of calculations of eigen values of Hess matrices [38]. In the second step *ab initio* calculations of the structures under investigation were carried out using the HF/6-31G* method with AM1 geometry. In addition an analysis of the population of the orbitals was carried out by the Hartree-Fock theory with natural orbitals using the G94NBO program [39]. We chose as reaction coordinates the distance between the atoms of the central carbon

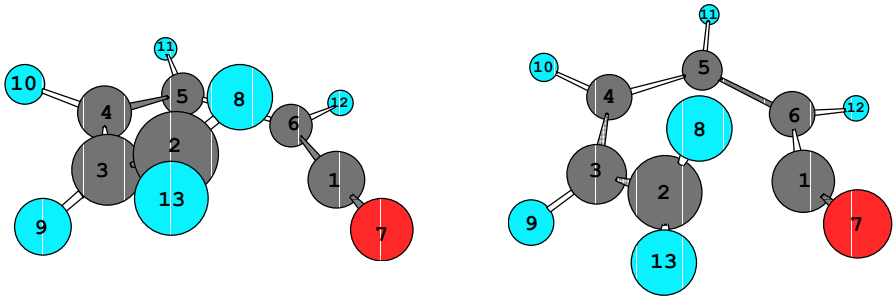
TABLE 1. Relative Energies (E_{rel}*) of the Starting Materials, the Transition States, and Final Products of the Cyclization of Cyclohexa-2,4-dienone **2**

Structure	E_{rel}, kcal/mol		
	AM1	PM3	HF/6-31G*/AM1
1	33.79	34.42	0.00
TS1	49.28	50.25	19.95
2	0.00	0.00	—

* E_{act} =15.49 (AM1), 19.95 (HF/6-31G*), and 15.83 kcal/mol (PM3).

atom of the ketene groups and the nitrogen/carbon terminus of the imino/methylene fragment, since this parameter experiences the greatest change during the course of the reaction (because this is the only bond formed during the reaction).

The energetic characteristics of the reactions are shown in Tables 1 and 2, and the results of the analysis of the electronic strictures of all the structures by the natural orbital method in Tables 3 (**1, TS1**), 4 (*E*-**3, TS2**), 5 and 6 (additional points), and 7 (*Z*-**3, TS3**). The geometrical parameters of the calculated structures are shown as 3D diagrams and the tables of geometric structures in Fig. 1 (**1, TS1**), 2 (*E*-**3, TS2**), and 3 (*Z*-**3, TS3**).

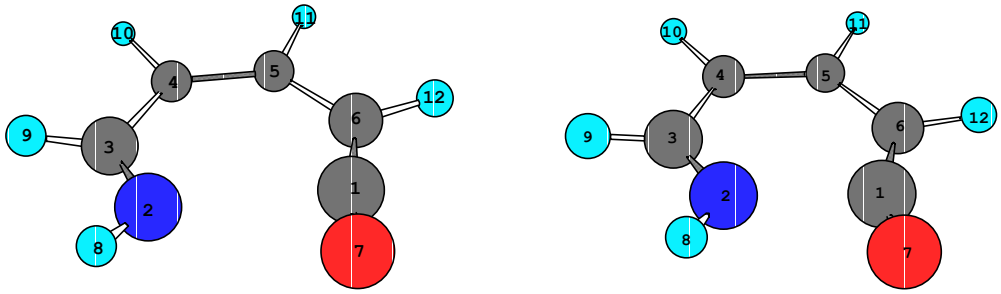


1 **TS1**

Fig. 1. Cyclization of compound **1**.

Geometric characteristics *r* (Å), α (deg), and τ (deg) calculated by the AM1 method

Characteristic	**1**	**2**	**TS1**
$r(C_{(1)}C_{(2)})$	2.926	1.507	2.069
$r(C_{(3)}C_{(2)})$	1.334	1.479	1.378
$r(C_{(3)}C_{(4)})$	1.447	1.344	1.405
$r(C_{(4)}C_{(5)})$	1.343	1.447	1.380
$r(C_{(5)}C_{(6)})$	1.434	1.346	1.397
$r(C_{(6)}C_{(1)})$	1.321	1.470	1.373
$r(C_{(1)}O_{(7)})$	1.189	1.238	1.202
$\alpha(C_{(6)}C_{(1)}O_{(7)})$	175.8	122.0	148.3
$\tau(C_{(2)}C_{(3)}C_{(4)}C_{(5)})$	49.5	0.7	30.4
$\tau(H_{(9)}C_{(3)}C_{(2)}H_{(8)})$	-178.5	-68.4	9.0
$\tau(C_{(4)}C_{(5)}C_{(6)}C_{(1)})$	-1.1	1.5	-11.8



***E*-3** **TS2**

Fig. 2. Cyclization of *E*-5-imino-1,3-pentadien-1-one **3**.

Geometric characteristics *r* (Å), α (deg), and τ (deg) calculated by the AM1 method

Characteristics	*E*-**3**	**4**	**TS2**
$r(C_{(1)}N_{(2)})$	2.642	1.411	2.082
$r(C_{(3)}N_{(2)})$	1.284	1.373	1.292
$r(C_{(3)}C_{(4)})$	1.455	1.373	1.443
$r(C_{(4)}C_{(5)})$	1.347	1.429	1.359
$r(C_{(5)}C_{(6)})$	1.425	1.358	1.412
$r(C_{(6)}C_{(1)})$	1.328	1.463	1.351
$r(C_{(1)}O_{(7)})$	1.185	1.247	1.196
$\alpha(C_{(6)}C_{(1)}O_{(7)})$	172.8	125.3	153.4
$\tau(C_{(2)}C_{(3)}C_{(4)}C_{(5)})$	-0.3	0.0	-0.1
$\tau(H_{(9)}C_{(3)}N_{(2)}H_{(8)})$	0.1	-0.1	0.0
$\tau(C_{(4)}C_{(5)}C_{(6)}C_{(1)})$	0.1	0.1	0.1

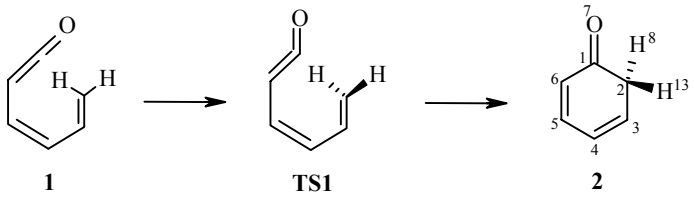
TABLE 2. Relative Energies (E_{rel}) of the Starting Material (**2** Isomer), the Corresponding Transition State and the Final Product of the Cyclization of Pyridin-2-one **4**

Structure	E_{rel}, kcal/mol*		
	AM1	HF/6-31G*//AM1	PM3
E-**3**	37.55	47.88	43.59
Z-**3**	38.02	54.65	43.39
4	0.00	0.00	0.00
TS2	42.38	45.12	42.44
TS3	70.87	79.07	65.94

* Pseudopericyclic mechanism: E_{act} (AM1) = 4.83 kcal/mol, E_{act} (HF/6-31G*//AM1) – without barrier, E_{act} (PM3) – without barrier; pericyclic mechanism: E_{act} = 32.85 (AM1), 24.42 (HF/6-31G*//AM1), 22.55 kcal/mol (PM3).

CYCLIZATION OF 1,3,5-HEXATRIEN-1-ONE

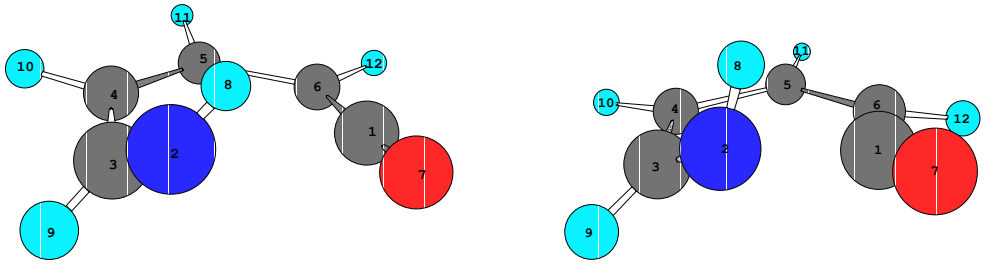
In the first stage of this work the cyclization of 1,3,5-hexatrien-1-one **1** into cyclohexa-1,3-dien-5-one **2** was calculated.



1 **TS1** **2**

The initial open form of **1** was localized with r ($C_{(1)}$–$C_{(2)}$) = 2.936 (AM1) and 3.035 Å (PM3). The geometry of the localised structure is non-planar with the terminal vinyl group out of the plane of the molecule, with the corresponding torsion angles $\tau(C_{(2)}C_{(3)}C_{(4)}C_{(5)})$ = 49.5 and $\tau(H_{(9)}C_{(3)}C_{(2)}H_{(8)})$ = 178.5° (AM1). The remaining carbon skeleton, including the terminal ketene group, lies in a single plane (Fig. 1).

The transition state **TS1** was localized with the reaction coordinates r ($C_{(1)}$–$C_{(2)}$) = 2.068 (AM1) and 2.108 Å (PM3). The geometry of the transition state is typical for a monorotator pericyclic process. From this point of view the mechanics of the cyclization process consists, from one side in the bending of the ketene group ($\alpha(C_{(6)}C_{(1)}O_{(7)})$ = 148.3° (AM1) and on the other side with the rotation of the vinyl group around an axis passing through the double bond $C_{(2)}C_{(3)}$ ($\tau(H_{(9)}C_{(3)}C_{(2)}H_{(8)})$ = -141.7°(AM1)).



***Z*-3** **TS3**

Fig. 3. Cyclization of *Z*-5-imino-1,3-pentadien-1-one **3**.

Geometric characteristics r (Å), α (deg), and τ (deg) calculated by the AM1 method

Characteristics	*Z*-**3**	**4**	**TS3**
$r(C_{(1)}N_{(2)})$	2.963	1.4108	1.957
$r(C_{(3)}N_{(2)})$	1.278	1.373	1.332
$r(C_{(3)}C_{(4)})$	1.463	1.373	1.414
$r(C_{(4)}C_{(5)})$	1.341	1.429	1.385
$r(C_{(5)}C_{(6)})$	1.434	1.358	1.392
$r(C_{(6)}C_{(1)})$	1.322	1.463	1.387
$r(C_{(1)}O_{(7)})$	1.184	1.247	1.200
$\alpha(C_{(6)}C_{(1)}O_{(7)})$	176.3	125.3	145.1
$\tau(N_{(2)}C_{(3)}C_{(4)}C_{(5)})$	51.5	0.0	31.3
$\tau(H_{(9)}C_{(3)}N_{(2)}H_{(8)})$	-179.1	-0.1	-144.6
$\tau(C_{(4)}C_{(5)}C_{(6)}C_{(1)})$	-7.9	0.1	-10.4

TABLE 3. Electronic Structures of Compound **1** and **TS1** (NO Method)

Bond, atoms	**1**			**TS1**		
	Orbital type	Occupancy	Energy	Orbital type	Occupancy	Energy
$C_{(2)}C_{(3)}$	$\sigma(sp^2–sp^2)$	1.9888	-0.97529	$\sigma(sp^2–sp^2)$	1.9879	-0.96281
	$\pi_{x,z}$	1.9561	-0.37771	$\pi_{x,y,z}$	1.6810	-0.3256
	—	—	—	$\pi_{y,z}$*	0.2598	0.17214
$C_{(1)}C_{(6)}$	$\sigma(sp–sp^2)$	1.9881	-1.0676	$\sigma(sp^2–sp^2)$	1.9825	-1.00594
	π_z	1.9267	-0.4126	π_z	1.7143	-0.33453
	π_z*	0.2006	0.2007	$\pi_{y,z}$ *	0.4201	0.12341
$C_{(1)}O_{(7)}$	$\sigma(sp–sp)$	1.9979	-1.4724	$\sigma(sp^2–sp)$	1.9943	-1.40515
	π_x	1.9924	-0.5790	$\pi_{x,z}$	1.9620	-0.56633
	—	—	—	$\pi_{y,z}$ *	0.2154	0.22098
$C_{(6)}C_{(5)}$	$\sigma(sp^2–sp^2))$	1.9686	-0.90064	$\sigma(sp^2–sp^2)$	1.9782	-0.93960
$C_{(5)}C_{(4)}$	$\sigma(sp^2–sp^2)$	19857	-0.96925	$\sigma(sp^2–sp^2)$	1.9824	-0.93780
	π_z	1.9359	-0.37030	π_z	1.7322	-0.34013
	π_z*	0.1068	0.24327	π_z*	0.2685	0.19731
$C_{(4)}C_{(3)}$	$\sigma(sp^2–sp^2)$	1.9805	-0.87579	$\sigma(sp^2–sp^2)$	1.9811	-0.92207
$O_{(7)}$	LP ($\sigma(sp)$)	1.9782	-0.99947	LP ($\sigma(sp)$)	1.9732	-0.94507
	LP (p_z)	1.7599	-0.45711	LP (p_y)	1.7651	-0.42022

The activation barrier for the cyclization was 15.49, 19.95, and 15.83 kcal/mol calculated by the AM1, HF/6-31-G*//AM1, and PM3 methods (Table 1). It should be noted that the values obtained by the AM1 and PM3 methods are quite close to the experimental value of the activation energy (145.2 kcal/mol) [40]. The cyclization reaction is exothermic: $\Delta\Delta H_{react}$ ~ 34 (AM1), 34 kcal/mol (PM3).

The NO method assigns the probable structure of the starting compound **1**: $\sigma(sp^2\text{-}sp^2)$-type orbitals for the $C_{(2)}–C_{(3)}$, $C_{(6)}–C_{(5)}$, $C_{(5)}–C_{(4)}$, and $C_{(4)}–C_{(3)}$ bonds, the $\sigma(sp–sp^2)$-type for the $C_{(1)}–C_{(6)}$ bond, the $\sigma(sp\text{-}sp)$-type for the $C_{(1)}–C_{(7)}$ bond, and 4 π-bonds $C_{(2)}–C_{(3)}$, $C_{(1)}–C_{(6)}$, $C_{(1)}–O_{(7)}$, and $C_{(4)}–C_{(5)}$. Two lone electron pairs of types $\sigma(sp)$ and $\pi(p_z)$ are placed on the oxygen atom.

The system is destabilized; some of the electron density is shifted into two anti-bonding orbitals of $\pi^*(p_z)$-type. In the formation of the first of these p_z-orbitals of atoms $C_{(4)}$ and $C_{(5)}$ contribute 48.69 and 51.31% respectively.

The second $\pi^*(p_z)$-orbital is formed from atoms $C_{(1)}$ and $C_{(6)}$ with contributions of 63.9 and 63.1%. As a result of rotation of the vinyl group the conjugation of the π-systems is destroyed. This circumstance is revealed by the mixing of the p_x-orbitals with p_z in the formation of the bonding $\pi(C_{(2)}–C_{(3)})$-orbital. The contributions of the p_x-orbitals of atoms $C_{(2)}$ and $C_{(3)}$ to this orbital are 0.8237 and 0.7124 respectively, whereas the contributions of the p_z-orbitals is 0.5569 and 0.6730. The order of the bond between the reaction centers $C_{(1)}$ and $C_{(2)}$ is 0.00755.

It may be noted when comparing the transition state **TS1** with the open form **1** that the basic changes occur at the perimeter of the π-system, which increase the destabilization of conjugation. The occupancy of the π-orbitals localized on the $C_{(2)}–C_{(3)}$, $C_{(1)}–C_{(6)}$, and $C_{(4)}–C_{(5)}$ bonds is decreased to 1.68101, 1.71432, and 1.73223 respectively. In addition p_y-orbitals are mixed in during the formation of the $\pi(C_{(2)}–C_{(3)})$-orbitals (the π_{xz}-orbital is converted into a π_{xyz}-orbital). In principle this destabilization results from steric tension of the conversion of the $\pi_x^*(C_{(1)}–O_{(7)})$-orbital into the $\pi_{xy}^*(C_{(1)}–O_{(7)})$-orbital as a result of mixing p_y-orbitals with the original p_x-orbitals.

In **TS1** the number of nonbonding orbitals is increased to four – $\pi_{yz}^*(C_{(1)}–O_{(7)})$, $\pi_{xyz}^*(C_{(2)}–C_{(3)})$, $\pi_{yz}^*(C_{(1)}–C_{(6)})$, and $\pi_z^*(C_{(5)}–C_{(4)})$. The occupancy of the last two is practically twice as large as in compound **1**. The occupancy of the remaining orbitals is 0.21537 and 0.25982 respectively. In the transition state no interaction at all is observed between atoms $C_{(1)}$ and $C_{(2)}$ although the bond order is increased to 0.201.

TABLE 4. Electronic Structures of *E*-**3** and **TS2** (NO method)

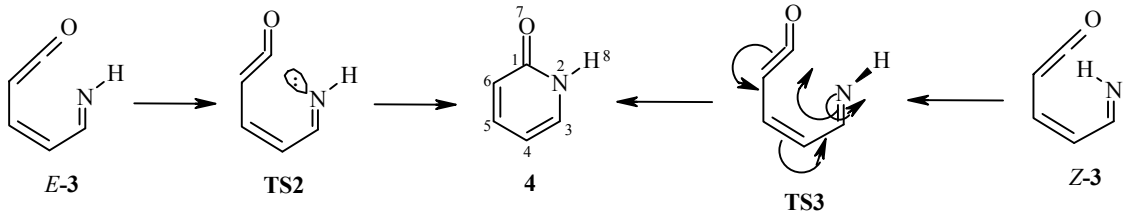
Bond, atom	*E*-**3**			**TS2**		
	Orbital type	Occupancy	Energy	Orbital type	Occupancy	Energy
$C_{(3)}N_{(2)}$	$\sigma(sp^2–sp^2)$	1.9948	-1.1533	$\sigma(sp^2–sp)$	1.9935	-1.1581
	π_z	1.9713	-0.4323	π_z	1.9686	-0.4557
	—	—	—	π_z*	0.16881	0.1844
$C_{(3)}C_{(4)}$	$\sigma(sp^2–sp^2)$	1.9816	-0.8846	$\sigma(sp^2–sp^2)$	1.9810	-0.8971
$C_{(4)}C_{(5)}$	$\sigma(sp^2–sp^2)$	1.9831	-0.9785	$\sigma(sp^2–sp^2))$	1.9828	–0.9647
	π_z	1.8926	-0.3612	—	—	—
	π_z*	0.1370	0.2233	—	—	—
$C_{(4)}C_{(5)}C_{(6)}$	—	—	—	3C(1)	1.9063	-0.4077
	—	—	—	3C*(1)	1.4454	-0.1577
$C_{(5)}C_{(6)}$	$\sigma(sp^2–sp^2)$	1.9717	-0.9158	$\sigma(sp^2–sp^2)$	1.9759	-0.9222
$C_{(6)}C_{(1)}$	$\sigma(sp^2–sp)$	1.9880	-1.0608	$\sigma(sp^2–sp)$	1.9865	-1.0331
	π_z	1.8846	-0.3977	—	—	—
	π_z*	0.2705	0.1966	—	—	—
$C_{(1)}O_{(7)}$	$\sigma(sp^2–sp)$	1.9981	-1.4726	$\sigma(sp^2–sp)$	1.9980	-1.4446
	$\pi_{x,y}$	1.9931	-0.5719	π_z	1.9964	-0.5619
	—	—	—	$\pi_{x,y}$	1.9932	-0.5538
				$\pi_{x,y}$*	0.2090	0.2263
$N_{(2)}$	—	—	—	π_z*	0.4656	0.1472
	LP (σ)	1.9776	-0.9883	LP (σ)	1.9726	-0.9499
$O_{(7)}$	LP ($\sigma(sp^2)$)	1.9994	-15.3606	LP ($\sigma(sp^2)$)	1.7697	-0.4684
	LP (p_z)	1.7309	-0.4399	—	—	—

CYCLIZATION OF 5-IMINO-1,3-PENTADIEN-1-ONE 3 INTO PYRIDIN-2-ONE 4

1-Azabutadienylketene **3**, like the diazoimine we studied previously [12], can presumably exist as *Z*- and *E*-isomers. If for cyclization compound *E*-**3** may be considered as a pericyclic monorotator and having a heteroelectrocyclic mechanism, then for the *Z*-isomer the heteroelectrocyclic mechanism will be hindered by the hydrogen atom of the imino group. So the different geometry of the *Z*- and *E*-isomers of compound **3** presumed the realization of different cyclization mechanisms.

A real minimum was found by the AM1 method for isomer *Z*-**3** separated from pyridin-2-one by a barrier of 4.8 kcal/mol. However all attempts to localise this structure by the PM3 method were unsuccessful. To optimize the open form of *E*-**3** "rolling" in the region of the minimum, the corresponding product of reaction was 1H-pyridin-2-one **4**. Similar behavior was noted for 5-oxo-2,4-pentadienal with optimization of the geometry by *ab initio* methods [24]. Analogously, *ab initio* calculations for isomer *E*-**3** (HF/6-31G*//AM1, Table 2) did not permit localization of a minimum on the potential energy surface corresponding to this structure.

The molecule of compound *E*-**3** is planar (see Fig. 2) with the torsion angles $\tau(C_{(2)}C_{(3)}C_{(4)}C_{(5)}) = 0.3$ and $\tau(C_{(1)}C_{(6)}C_{(5)}C_{(4)}) = 0.1°$ (AM1). The distance between the reaction centers r ($C_{(1)}$–$N_{(2)}$) equals 2.642 Å (AM1).



E-**3** **TS2** **4** **TS3** *Z*-**3**

TABLE 5. Results of the Analysis of the Electronic Structure (NO Method) with Additional Points for the Cyclization of 5-Imino-1,3-pentadien-1-one **3**

Bond, atom	$r(N_{(2)}C_{(3)})$ = 1.6 Å			Bond, atom	$r(N_{(2)}C_{(3)})$ = 1.7 Å			$r(N_{(2)}C_{(3)})$ = 1.8 Å		
	Orbital type	Occupancy	Energy		Orbital type	Occupancy	Energy	Orbital type	Occupancy	Energy
$C_{(1)}N_{(2)}$	$\sigma(sp^3–sp^2)$	1.98439	-0.86492	$C_{(1)}N_{(2)}$	$\sigma(sp^3–sp^3)$	1.97985	-0.78846	$\sigma(sp^3–sp^3)$	1.97409	-0.7233
$N_{(2)}$	LP (p_z)	1.65693	-0.35921	$N_{(2)}C_{(3)}$	$\sigma(sp^2–sp^2)$	1.99183	-1.13259	$\sigma(sp^2–sp^2)$	1.99231	-1.14691
$N_{(2)}C_{(3)}$	$\sigma(sp^2–sp^2)$	1.99122	-0.11570		π_z	1.94837	-0.48284	π_z	1.9579	-0.4779
$C_{(3)}C_{(4)}$	$\sigma(sp^2–sp^2)$	1.98263	-0.95623	$C_{(3)}C_{(4)}$	$\sigma(sp^2–sp^2)$	1.98211	-0.94452	$\sigma(sp^2–sp^2)$	1.98163	-0.93093
	π_z	1.79305	-0.34880	$C_{(4)}C_{(5)}$	$\sigma(sp^2–sp^2)$	1.98178	-0.92812	$\sigma(sp^2–sp^2)$	1.98209	-0.94092
$C_{(4)}C_{(5)}$	$\sigma(sp^2–sp^2)$	1.98152	-0.91824	$C_{(4)}C_{(5)}C_{(6)}$	3C(1)	1.89047	-0.40964	3C(1)	1.88339	-0.41076
$C_{(5)}C_{(6)}$	$\sigma(sp^2–sp^2)$	1.98198	-0.96557		3C*(1)	1.37073	-0.14500	3C*(1)	1.42521	-0.1533
	π_z	1.80753	-0.35003	$C_{(5)}C_{(6)}$	$\sigma(sp^2–sp^2)$	1.98100	-0.95847	$\sigma(sp^2–sp^2)$	1.97971	-0.94781
$C_{(6)}C_{(1)}$	$\sigma(sp^2–sp)$	1.98424	-0.93591	$C_{(6)}C_{(1)}$	$\sigma(sp^2–sp)$	1.98388	-0.95750	$\sigma(sp^2–sp)$	1.98322	-0.9804
$C_{(1)}O_{(7)}$	$\sigma(sp^2–sp)$	1.99699	-1.35246	$C_{(1)}O_{(7)}$	$\sigma(sp^2–sp)$	1.99678	-1.37799	$\sigma(sp^2–sp)$	1.99597	-1.39865
	π_z	1.99208	-0.50449		π_z	1.99299	-0.5167	π_z	1.99407	-0.52864
$O_{(7)}$	LP ($\sigma(sp)$)	1.97631	-0.91839	$O_{(7)}$	LP ($\sigma(sp)$)	1.97484	-0.92187	LP ($\sigma(sp)$)	1.97344	0.92639
	LP (p_y)	1.86549	-0.40509		LP (p_y)	1.83269	-0.40476	LP (p_y)	1.78741	-0.40019

TABLE 6. Electronic Structures of Isomer *Z*-**3** and **TS3** (NO Method)

Bond, atom	*Z*-**3**			**TS3**		
	Orbital type	Occupancy	Energy	Orbital type	Occupancy	Energy
$N_{(2)}C_{(3)}$	$\sigma(sp^2\text{-}sp^2)$	1.9955	-1.1585	$\sigma(sp^2\text{-}sp^2)$	1.9934	-1.1166
	$\pi_{x,y}$	1.9743	-0.4456	$\pi_{x,y,z}$	1.7223	-0.4029
	—	—	—	$\pi_{x,y,z}$*	0.2949	0.1386
$C_{(3)}C_{(4)}$	$\sigma(sp^2\text{-}sp^2)$	1.9861	-0.8957	$\sigma(sp^2\text{-}sp^2)$	1.9867	-0.9408
$C_{(4)}C_{(5)}$	$\sigma(sp^2\text{-}sp^2)$	1.9834	-0.9879	$\sigma(sp^2\text{-}sp^2)$	1.9829	-0.9469
	π_z	1.9328	-0.3913	π_z	1.7162	-0.3495
	π_z*	0.10259	0.23003	π_z*	0.2799	0.1781
$C_{(5)}C_{(6)}$	$\sigma(sp^2\text{-}sp^2)$	1.9691	-0.9193	$\sigma(sp^2\text{-}sp^2)$	1.9798	-0.9798
$C_{(6)}C_{(1)}$	$\sigma(sp^2\text{-}sp)$	1.9882	-1.0823	$\sigma(sp^2\text{-}sp)$	1.9850	-1.0127
	π_z	1.9194	-0.4249	$\pi_{x,y,z}$	1.6739	-0.3283
	π_z*	0.25039	0.18584	$\pi_{x,y,z}$*	0.4161	0.1100
$C_{(1)}O_{(7)}$	$\sigma(sp\text{-}sp)$	1.9981	-1.4896	$\sigma(sp^2\text{-}sp)$	1.9956	-1.4380
	$\pi_{x,y}$	1.9926	-0.5932	$\pi_{y,z}$	1.9482	-0.5548
	—	—	—	$\pi_{y,z}$*	0.2283	0.1938
$N_{(2)}$	LP($\sigma(sp^2)$)	1.9539	-0.5429	LP($\sigma(sp^2)$)	1.9601	-0.5502
$O_{(7)}$	LP ($\sigma(sp)$)	1.9788	-1.0138	LP ($\sigma(sp)$)	1.9737	-0.9549
	LP (p_z)	1.7548	-0.4705	LP (p_y)	1.7306	-0.4219

The transition state **TS2** corresponding to the cyclization of *E*-**3** was localized at a point with *r* ($C_{(1)}$–$N_{(2)}$) = 2.082 Å (here and below data cited are from the AM1 method). In moving along the reaction path all the heavy atoms of the molecule remain in the same plane. In addition to the planarity of the heavy atom skeleton retained in **TS2** in comparison with molecule *E*-**3**, the absence of movement of the hydrogen atoms should be noted which favors the monorotator mechanism of cyclization. The most important changes in **TS2** are those of *r* ($C_{(1)}$–$N_{(2)}$) = 2.082 Å and the angle $O_{(7)}C_{(1)}C_{(6)}$ (153.4°). For the *E*-**3** starting material and the cyclization product **4** these values are respectively 2.642 Å/172.8° and 1.411 Å/153.4°. The cyclization process may be described as the approach of the reaction centers $C_{(1)}$ and $N_{(2)}$ accompanied by bending of the ketene group at the angle $O_{(7)}C_{(1)}C_{(6)}$. Rotation of the terminal group of the π-system does not occur. Thus the geometrical parameters of **TS2** are in agreement with a heteroelectrocyclic non-rotatory mechanism for the cyclization of isomer *E*-**3**.

According to the AM1 method, isomer *Z*-**3** is ~0.5 kcal/mol less stable than isomer *E*-**3**. The cyclization reaction is significantly exothermic: $\Delta\Delta H_{react}$ ~38 (AM1), 43 (PM3), and 50 kcal/mol (HF/6-31G*//AM1). Cyclization of compound *Z*-**3** into compound **4** proceeds *via* a considerably higher barrier (20-30 kcal/mol, Table 2) than is characteristic for normal pericyclic reactions*.

It should be noted that cyclization of compound *Z*-**3**, which is an aza analog of compound **1**, occurs with a much higher barrier than for **1**. This my be explained by the large steric strain which exists in the transition state **TS3** (see also the geometry of the transition states in Fig. 1 and 3).

According to calculations by methods AM1 and PM1, the geometry of isomer *Z*-**3** is not planar (Fig. 3). Steric repulsion between the hydrogen atom of the imino group and the ketene function leads to an increase in the distance $C_{(1)}$–$N_{(2)}$ in isomer *Z*-**3** to 2.693 (AM1) in comparison to 2.642 A for isomer *E*-**3**, and also to bending of the molecular skeleton and deviation of atoms from the unit plane. The imino group is displaced from the plane containing atoms $C_{(3)}$, $C_{(4)}$, and $C_{(5)}$ ($\tau(C_{(5)}C_{(4)}C_{(3)}N_{(2)})$ = 51.1 and $\tau(C_{(5)}C_{(4)}C_{(3)}H_{(9)})$ = -130.5°).

* For comparison: 1,4-cyclization of vinylketene to cyclobutenone [13] occurs with a major barrier, E_{act} = 32.85 kcal/mol, according to MP4//HF/6-31G** calculations.

The transition state **TS3** for the cyclization of isomer *Z*-**3** into compound **4** was localized at a point with the reaction coordinate *r* ($C_{(1)}$–$N_{(2)}$) = 1.965 (AM1) and 2.011 A (PM3). Comparing isomer *Z*-**3** with **TS3**, one can note that shift of the nitrogen atom of the imino group into plane of the heavy atoms and a shift of the hydrogen away from this plane ($\tau(C_{(5)}C_{(4)}C_{(3)}N_{(2)})$ = 0.0, $\tau(C_{(4)}C_{(3)}N_{(2)}H_{(8)})$ = 42.7, and $\tau(H_{(10)}C_{(3)}N_{(2)}H_{(8)})$ = -144.6°). According to the sum of the valence angles around it ($\Sigma\alpha$ = 359.7°), atom $C_{(3)}$ is not pyramidalized. Thus cyclization of isomer *Z*-**3** appears as a process of bending of the valence angle $O_{(7)}C_{(1)}C_{(6)}$ with a simultaneous rotation of the imino group around an axis passing through the $C_{(3)}$=$N_{(2)}$ double bond, and an approach of the reaction centers $C_{(1)}$ and $N_{(2)}$. Consequently the reaction may be described as a monorotator electrocyclic.

A characteristic of heteroelectrocylic reactions is the participation of lone electron pairs of a heteroatom not conjugated with the π-system (in our case, the nitrogen atom of the imino group) in the formation of the new σ-bond. This sharply distinguishes this type of reaction from classical pericyclic reactions in which a π-bond is broken as the result of rotation of the terminal unit of the system. Therefore the two types of mechanism should be strictly differentiated according to the nature of the electronic structure of the transition states.

According to data derived from the NO method, the electronic structure of isomer *E*-**3** corresponds precisely to the classical valence formula, i.e., σ(sp^2-sp^2) bonds between atoms $N_{(2)}$ and $C_{(3)}$, $C_{(3)}$ and $C_{(4)}$, $C_{(4)}$ and $C_{(5)}$, $C_{(5)}$ and $C_{(6)}$; σ(sp^2-sp) and σ(sp-sp) bonds between $C_{(1)}$ and $C_{(6)}$ and $C_{(1)}$ and C(7); π_z-orbitals between atoms $N_{(2)}$ and $C_{(3)}$, $C_{(4)}$ and $C_{(5)}$, $C_{(1)}$ and $C_{(6)}$, and π_{xy} ($C_{(1)}$–$O_{(7)}$), and orbital lying in the plane of the molecule, but not perpendicular to it. In addition $N_{(2)}$ has unpaired electrons of type σ(sp^2) and $O_{(7)}$ has two lone pairs of types σ(sp) and π(p_z). Analysis of the occupancy of the π_z*-orbitals indicates delocalisation of the π-electrons (Table 4). The small occupancy of the π_z*($C_{(4)}$–$C_{(5)}$)-orbital is explained by migration of electron density from the π_z($N_{(2)}$–$C_{(3)}$)- and π_z($C_{(1)}$–$C_{(6)}$)-orbitals. In its turn the π_z*($C_{(1)}$–$C_{(6)}$) is filled from the π_z($C_{(4)}$–$C_{(5)}$)- and p_z($O_{(7)}$)-orbitals.

The electronic structures of isomers *Z*-**3** and *E*-**3** are basically the same (see Table 6). But as a result of the rotation of the imino group in isomer *Z*-**3** relative to the $C_{(3)}$–$C_{(4)}$ bond the p_x-orbital is mixed into the $N_{(2)}C_{(3)}$ π-bond.

In **TS2,** in comparison with isomer *E*-**3**, the filling of the σ-skeleton remains basically unchanged (Table 4). The most notable change is the decrease in the *p*-character of the sp^2-hybrid $N_{(2)}$, determined by σ-bonding to $C_{(3)}$, and corresponding to the increase in *p*-character of the lone pair of the nitrogen atom. The interaction between atoms $C_{(1)}$ and $N_{(2)}$, which appears as the formation of a new σ-bond in the product, is much too weak to be described as an orbital by the NO method. However some linkage does exist between these two atoms which leads to an increase in bond order from 0.016 in isomer *E*-**3** to 0.0150 in **TS2.** This is important given that this linkage is exclusively as a result of participation of the lone electron pair of σ-type belonging to the nitrogen atom. This is also indicated by the decreased occupancy of the π_z($N_{(2)}$–$C_{(3)}$)-orbitals perpendicular to the plane of the molecule in **TS2** and the isomer *E*-**3** (1.9686 vs. 1.9713). While the σ-framework and the π_z($N_{(2)}$–$C_{(3)}$)-orbital in **TS2** remain virtually unchanged, the π-system of the remaining heavy atoms undergoes a considerable change. The p_z-orbital of $C_{(1)}$ and the lone pair of π-type of $O_{(7)}$ take part in the formation of the new π_z($C_{(1)}$–$O_{(7)}$)-orbital. In **TS2** the p_z-orbital of $C_{(6)}$ interacts with the π_z($C_{(4)}$–$C_{(5)}$)-orbital in **TS2** to form bonding and nonbonding three-centered orbitals (3C and 3C*, Table 4). The π_z($C_{(1)}$–$O_{(7)}$)-orbital still lies in the plane in **TS2**, but the values of the orbital coefficients of $C_{(1)}$ and $O_{(7)}$ are changed: they are decreased (0.5 to 0.4) and increased (0.8 to 0.9) respectively. In compound **4** this orbital corresponds to an lone pair of *p*-type of atom $O_{(7)}$, lying in the plane. The **TS2** π-system is considerably destabilized as is indicated by the occupancy of the anti-bonding π_z-orbitals (Table 4), while the three-centered orbital 3C(($C_{(4)}C_{(5)}C_{(6)}$) reacts basically as an electron donor. The basic electron donor for the anti-bonding π_{xy}*-orbital is the lone electron pair of atom $N_{(2)}$.

In other words, the σ($C_{(1)}$–$N_{(2)}$) bond and the lone electron pair of atom $O_{(7)}$ will be formed as a result of the interaction of two natural molecular orbitals (NMO). The basic role of the lone electron pair is to serve in the assembly of natural localized molecular orbitals (NLMO) formed from the corresponding NMO. While in

compound *Z*-**3** the NLMO corresponding to the lone electron pair on nitrogen is practically completely formed (97%) from the corresponding NMO and is 97% localized on $N_{(2)}$, in **TS2** the corresponding NMO is localized 88% on the nitrogen and 7% on atom $C_{(1)}$. The reason for this is the delocalization of the nitrogen lone electron pair, which considerably decreases the occupancy of the orbital from 2.00 to 1.77.

Analysis by the NO method of additional points lying on the path from **TS2** to compound **4** shows that the new σ-bond is formed after complete formation of **TS2** (Table 5) at intersection of the coordinates between 2.082 and 1.800 A. At the point with coordinate 1.800 A there is a completed orbital, corresponding to this bond and with an order of 0.4927. The final redistribution of electron density is achieved at a point with a reaction coordinate of 1.600 A. The electronic structure at this point corresponds to the classical formula of 1H-pyridin-2-one **2a**.

TS3 has a completely different organisation of electrons in comparison with **TS2**. The most important characteristic is the unchanged occupancy of the orbitals (1.95 and 1.96 in *Z*-**3** and **TS3**) corresponding to the lone electron pair of the N of the imino group. It follows from this that the lone electron pair of atom $N_{(2)}$ does not participate in the formation of the new bond. There is a change in occupancy of this orbital in **TS3** (it decreases significantly from 1.97 in isomer *Z*-**3** to 1.72 in **TS3**, Table 6), whereas in **TS2** there is practically no change in $\pi_z(N_{(2)}–C_{(3)})$ in moving along the reaction coordinate. In **TS3** the antibonding π-orbitals ($C_{(1)}–O_{(7)}$) and ($C_{(1)}–C_{(6)}$) emerge as the basic acceptors of electrons.

Moreover in **TS3** the $\pi(C_{(1)}–O_{(7)})$-orbital is transformed from π_{xy} to π_{yz} while the oxygen lone electron pair is converted from p_y to p_z. Thus a completely formed lone electron pair of p_y-type is found on the oxygen in **TS3**. As in **TS2**, the interaction between $N_{(2)}$ and $C_{(1)}$ is very weak, for it to be described in terms of an NO. The order of the bond between the reaction centers is 0.19 as a result of overlap with the $\pi_z(N_{(2)}–C_{(3)})$-orbital.

This study shows that the semiempirical AM1 and PM3 methods are suitable for the study of the mechanism of cyclization of heteroatomic π-conjugated systems containing a ketene fragment.

According to the comparative analysis of the geometric parameters of compounds **1**-**4** and **TS1**-**TS3**, the processes of cyclization of 1,3,5-hexatrien-1-one **1** and 5-imino-1,3-pentadien-1-one *Z*-**3** have the following character: they occur by a monorotatory process which requires the rotation of only one end group (imine or vinyl). Cyclization of ketene *E*-**3** differs fundamentally from the preceding reactions: it has a planar transition state and rotation of the terminal groups of the π-system does not occur.

Cyclization of compound *E*-**3** occurs with a very small barrier, not exceeding 8 kcal/mol (AM1 method) or with no barrier at all (PM3). In contrast with isomer *E*-**3**, cyclization of isomer *Z*-**3** occurs with a considerably higher activation energy: 32.85 kcal/mol (AM1 method) or 22.55 kcal/mol (PM3 method).

It is shown with the help of the NO method that in the cyclization of compound **1** into compound **2** and of isomer *Z*-**3** into compound **4** the new σ-bonds are formed from the electrons of the existing π-systems. A complete difference in the cyclization of the ketene *E*-**3** is the participation of the lone electron pair of the nitrogen of the imino group, oriented on the side of the ketene group, in the formation of the new σ-bond.

Thus all three criteria, structural, energetic, and orbital , indicate separately the importance of a heteroelectrocyclic mechanism for the cyclization of 5-imino-1,3-pentadien-1-one *E*-**3**.

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