Heteroatom Chemistry
Volume 2, Number 2, 1991

Molecular Modeling of the Wittig Olefination Reaction: Part 2†: A Molecular Orbital Approach at the MNDO-PM3 Level

Frank Marí, Paul M. Lahti, and William E. McEwen*

Department of Chemistry, University of Massachusetts, Amherst, MA, 01003, U.S.A.

Received 10 October 1990.

ABSTRACT

We have shown that the MNDO-PM3 semiempirical molecular orbital method is capable of yielding calculated structures of oxaphosphetanes and ylides that are comparable with the experimentally known structures.

The MNDO-PM3 method also reproduces the geometric and thermodynamic parameters of the "mythical Wittig half-reaction", previously calculated using a more elaborate and costly ab initio *molecular orbital approach. In addition, using the SADDLE routine, we were able to find a transition state for this half-reaction. This transition state resembles geometrically the transition state found using the ab initio approach (4-31G* level). The energy of activation was calculated to be 9.2 kcal/mole, which is fairly comparable with the ab initio result of 5.2 kcal/mole.*

According to our calculations, and in general agreement with findings of Volatron and Eisenstein [11], the mythical Wittig reaction would be expected to proceed through a planar transition state for the cycloaddition of the ylide and the aldehyde in a process that superficially seems to be a synchronous one. However, an analysis of the evolution of the bond orders and the localized molecular orbitals throughout the reaction indicates that the P–O bond has not been formed in the transition state, whereas the C–C bond is about 40% formed. Therefore, the mythical Wittig half-reaction is best described as a very asynchronous cycloaddition (a borderline two step mechanism) with a planar geometry in the transition state, composed of a multi-centered mP–C–C–O bond orbital and with the phosphorus and the oxygen atoms sharing a strong attractive charge interaction. A similar description results from computations of the Wittig reactions of $H_3P{=}CHCH_3$ *and* $(C_6H_5)_3P{=}CHCH_3$ *with* H_3CCHO*, which is inconsistent with the Vedejs geometry.*

INTRODUCTION

The Wittig olefination reaction (Scheme 1) involves the reaction of an ylide (**1**) with an aldehyde or ketone to form an alkene (or a mixture of geometrically isomeric alkenes) and a phosphine oxide. The mechanism of this reaction has been under study since its discovery and several mechanisms have been considered; however, none of them provides completely adequate evidence for the intermediates or transition states involved or for the stereochemistry of alkene formation. The mechanisms presently extent in the literature cannot account for all of the experimental evidence accumulated throughout the years [2].

Perhaps the most striking mechanistic feature of the salt-free reaction is the stereoselectivity of alkene formation (where pertinent). The stereoselectivity, which also largely determines its synthetic value, is highly dependent on the substituents bonded to the ylidic carbon (R^1) and to the phosphorus atom. According to the nature of these substituents, the Wittig reaction has been shown to yield preferentially Z-alkenes for unstabilized ylides where R^1 = alkyl and R = phenyl (the most common case), mixtures of the Z and E alkenes for semistabilized ylides (R^1 = phenyl, vinyl, propargyl, –F), and mainly E-alkenes for stabilized ylides

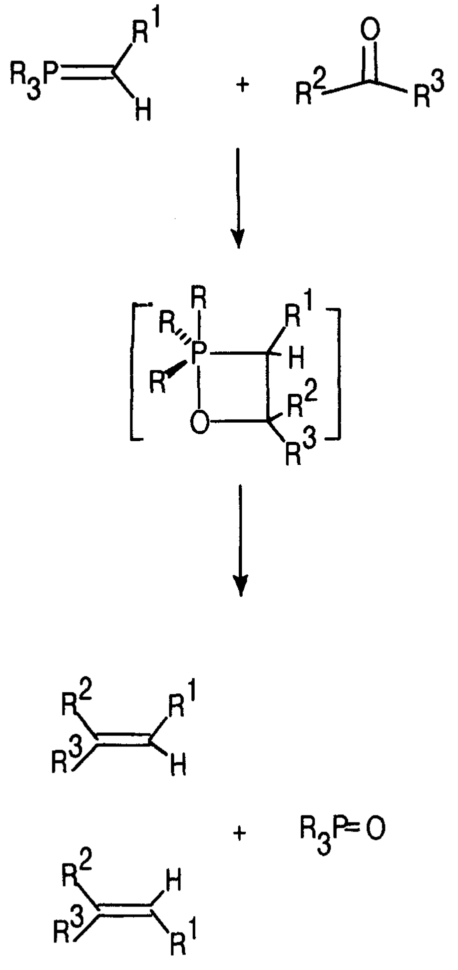
---

*To whom correspondence should be addressed.

†For Part 1, see Ref. [1].

This paper is dedicated to Professor Dr. Rolf Appel on the occasion of his 70th birthday.

1042-7163/91/$3.50 + .25



SCHEME 1

(R^1 = $-COOCH_3$, $-CN$). There is no general mechanism that presently provides sufficient hard evidence to accommodate all of these observations.

The only intermediates that have been spectroscopically observed are the oxaphosphetanes (**2**) and even that holds true only for cases in which unstabilized ylides (R^1 = alkyl) are involved in the reaction. This experimental observation does not necessarily rule out any other transient intermediate whose life time is too short compared to the time scale of the spectroscopic technique used for its detection; neither does it prove that oxaphosphetanes are mandatory intermediates for those reactions in which semistabilized and stabilized ylides are involved. Oxaphosphetanes have not been observed for the latter two cases [3]. Nevertheless, it appears to be a reasonably safe assumption that oxaphosphetanes are transient intermediates in those reactions where semistabilized and stabilized ylides are involved.

Schlosser has suggested that, for the case where an unstabilized ylide is used and where the substituents on the phosphorus atom are phenyl groups, an oxaphosphetane-like transition state may be responsible for the Z-alkene stereoselectivity of the Wittig reaction [4] (Figure 1). According to Schlosser, the Z-oxaphosphetane-like transition state (for that matter the Z-oxaphosphetanes themselves) are more stable than their E-counterparts. Vedejs has argued that Schlosser, by proposing this "leeward" approach, has misinterpreted the steric interaction of substituent groups of the aldehyde with the phenyl groups of the phosphorus; instead, he has proposed that the reaction proceeds through a four-center puckered asynchronous cycloaddition where steric strain and the phosphorus rehybridization may favor transition states that lead to the Z-oxaphosphetane (Figure 2) in preference to the "E" counterpart [5].

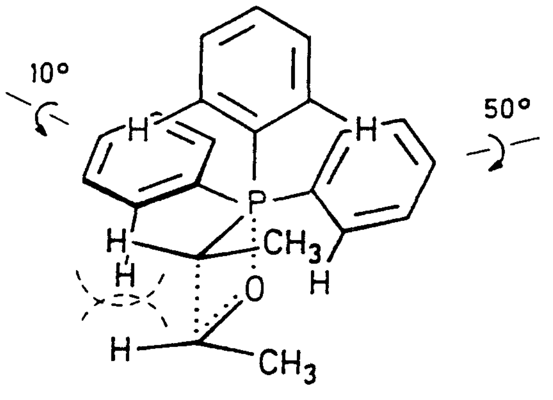
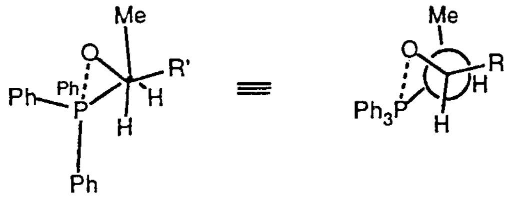


FIGURE 1 The "leeward" approach proposed by Schlosser for the transition state of the Wittig reactions of unstabilized ylides, to explain the "CIS" stereoselectivity.

Experimental evidence indicates that, for the case of unstabilized ylides, the Z-oxaphosphetanes form faster than the E-oxaphosphetanes [6]. The reason for this behavior is still unclear; however, there seems to be a general agreement that the key factor that determines the stereoselectivity of the Wittig reaction must lie somewhere in the reaction path that leads to the formation of the oxaphosphetane, most likely a transient intermediate or a transition state, which is not observable spectroscopically. Since such nonobservable species are conceivably responsible for the stereoselectivity ob-

FIGURE 2 The four-center puckered transition state of the asynchronous cycloaddition of the ylide to an aldehyde, proposed by Vedejs to explain the "CIS" stereoselectivity of the Wittig reactions of unstabilized ylides.



served, the use of theoretical methods may presently be the only plausible way to unravel the mystery.

Several theoretical studies have been reported on the Wittig reaction using different levels of theory [7–11]. In particular, the use of semiempirical methods (CNDO and MNDO) [7–10] has been shown not to be very trustworthy for the modeling of this reaction. Perhaps the reason why semiempirical methods have failed in the past is because of the known problems that these methods have in the treatment of hypervalent compounds; in the present connection, in particular, the Wittig reaction involves the chemistry of phosphorus compounds (ylides and oxaphosphetanes) in their hypervalent states and different hybridizations. Furthermore, semiempirical methods have been shown in the past to present severe difficulties in finding the transition states of the reactions to be modeled. Fortunately, recent advances in the development of parameters have yielded a new set of parameters that are included in the new MNDO-PM3 method (Modified Neglected Diatomic Overlap, Parametric Method 3) [12,13]. This new method allows hypervalent systems to be treated with accuracies comparable to nonhypervalent compounds. Also, new routines for the systematic search for transition states have appeared in the literature since the previous theoretical studies mentioned above were published [14].

We have recently reported the results of applying empirical (Modified MMX87 force field) and semiempirical (MNDO) theoretical methods to model the oxaphosphetane intermediates of Wittig reactions [1]. In an extension of our previous work, we are now attempting to model the Wittig reaction by the exclusive use of the semiempirical molecular orbital methods that make use of the New MNDO-PM3 hamiltonian.

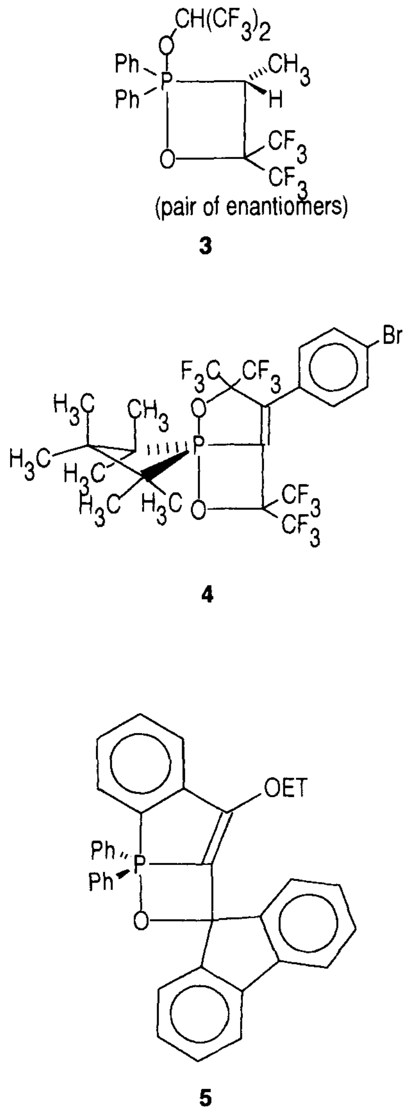
METHODOLOGY

The MOPAC [15] (Ver. 5.0) molecular orbital package utilizing the MNDO-PM3 hamiltonian was used for semiempirical MO calculations. The starting geometries for all of these semiempirical calculations are the minimized geometries of the MMX89 [16] force field.

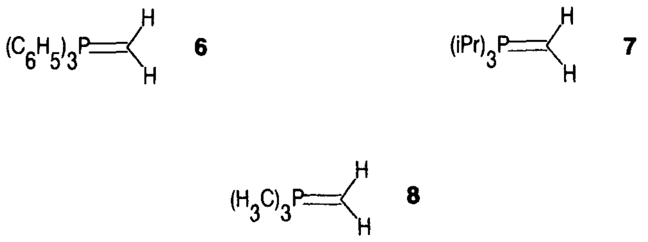
The putative transition states of the "mythical Wittig reaction" (Scheme 4) were found using the SADDLE routine implemented in MOPAC v5.0 [14]. The systems were characterized as transition states by the presence of one and only one negative force constant in the Hessian matrix of a force calculation [15]. To test for possible diradicaloid character of the transition states, a hypothesis recently introduced by one of us [17–19], we performed the calculations using the Unrestricted Hartree-Fock hamiltonian and the Configuration Interaction (C.I.) procedure [20]. The localized molecular orbitals (LMOs) for the reactants, products, and transition states were found using the Perkins–Stewart method implemented in MOPAC v5.0 [28]. Bond orders and valencies were calculated using the BONDS routine implemented in the same program [29]. The electron density map of the transition state was produced with the use of the program DENSITY [32].

Input files were generated using the graphics interface of PCMODEL-PI v3.0 (Serena Software, Bloomington, IN). The calculations were carried out on a DEC VAX-6210 computer at the University of Massachusetts University Computer Center.

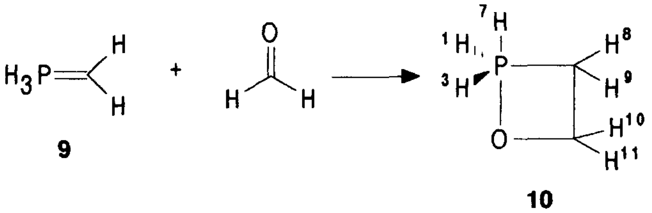
As a test for the reliability of our methods to predict the molecular structures of the intermediates involved in the Wittig reaction, calculations were performed on the known oxaphosphetanes, **3** [21], **4** [22], and **5** [23], the X-ray crystal structures of which have been determined (Scheme 2), and on



SCHEME 2



SCHEME 3



The numbers used as superscripts for the hydrogen atoms of the oxaphosphetane correspond to the numbers given in Figure 8.

SCHEME 4

ylides **6** [24], **7** [25], and **8** [26], which have also been isolated, and whose structures have been determined by use of X-ray crystallography or electron diffraction, respectively (Scheme 3).

It has been determined experimentally, under salt-free, low temperature conditions, that the key step that determines the stereoselectivity of most Wittig reactions is the one in which the oxaphosphetane is formed [2]. Thus, as a general approach we are considering only a "Wittig half-reaction", i.e., only the reaction of the ylide with an aldehyde to form an oxaphosphetane, as a model to attempt to explain mechanistically the observed stereoselectivity.

Previous theoretical studies of the Wittig reaction at the ab initio level of theory [10, 11] have made use of a "mythical Wittig reaction" as a model (Scheme 4), since the computational time required to perform full optimizations of all the species involved is the minimum for this model. We have used the same "reaction" to calibrate our methodology. Specifically, we have performed MNDO-PM3 calculations on the "Wittig half-reaction" of the mythical system in order to compare the energetics and the geometric correlations of the species involved in this "reaction" at the different levels of theory.

RESULTS AND DISCUSSION

The correlation between the experimental geometries (bond angles and lengths) of the four-membered ring of the oxaphosphetanes **2**, **3**, and **4** and the calculated values by MNDO-PM3 are shown in Figure 3 and Figure 4 and also in Table 1. Unlike our previous molecular modeling approach using the modified MMX87 force field, no assumptions were made about any of the bond lengths, and the values obtained by the MNDO-PM3 method are based on a full optimization of the structures. A good agreement for both bond lengths and bond angles between the experimental and calculated values can be found, although the MNDO-PM3 method tends to overestimate the P–C bond length in the oxaphosphetane ring. We have previously pointed out [1] the unusual nature of these particular oxaphosphetanes (**3–5**) and the expected divergence between the molecular structure of a compound in a single crystal (experimental requirement for an X-ray structure determination) and the molecular structure of a compound in the gas phase with motionless molecules, conditions assumed by the MNDO-PM3 method.

Likewise, the ylides of known structures show a good agreement between the experimental and calculated geometrical parameters (bond lengths and angles), especially the bond lengths (Figure 3 and Figure 4 and also in Table 2). Unlike the oxaphosphetanes, which are relatively rigid structures due to the presence of the four-membered ring, the ylides appear to be more flexible and more conformations seem to be possible. This is reflected in the scatter observed in the angle correlations (Figure 4, calculated vs. experimental) of ylides **6** and **7**. On the other hand, ylide **8**, whose structure was determined experimentally by the use of electron diffraction in the gas phase, shows a good correlation with the calculated structure based on the MNDO-PM3 method. Again, the small discrepancies found between the calculated and experimental molecular parameters seem to arise from the comparison of a solid state structure with a calculated structure based on the assumption that the molecules are motionless and in the gas phase.

The results shown above indicate that the MNDO-PM3 method may be suitable to model the Wittig reaction. Previous calculations have been performed at the ab initio level of theory (STO-3G[10] and 4-31G*[11]) on the "mythical Wittig reaction." Applying the MNDO-PM3 method to the same model reaction, we found a good geometrical (bond lengths and bond angles) correlation between the oxaphosphetane structure based on the highest ab initio level of theory so far computed for this intermediate and the bond lengths and bond angles calculated using the MNDO-PM3 method (Table 3). The only noticeable discrepancy is found to be the P–H bond lengths for both positions (axial and equatorial) in the trigonal bipyramid of P(V); the MNDO-PM3 method tends to underestimate these bond distances (i.e. P-Hax = 1.438 Å versus P-Heq = 1.389 Å at the 4-31G* level of theory, whereas by using MNDO-PM3, these distances are found to be 1.26 Å and 1.24 Å, respectively). On the other hand,

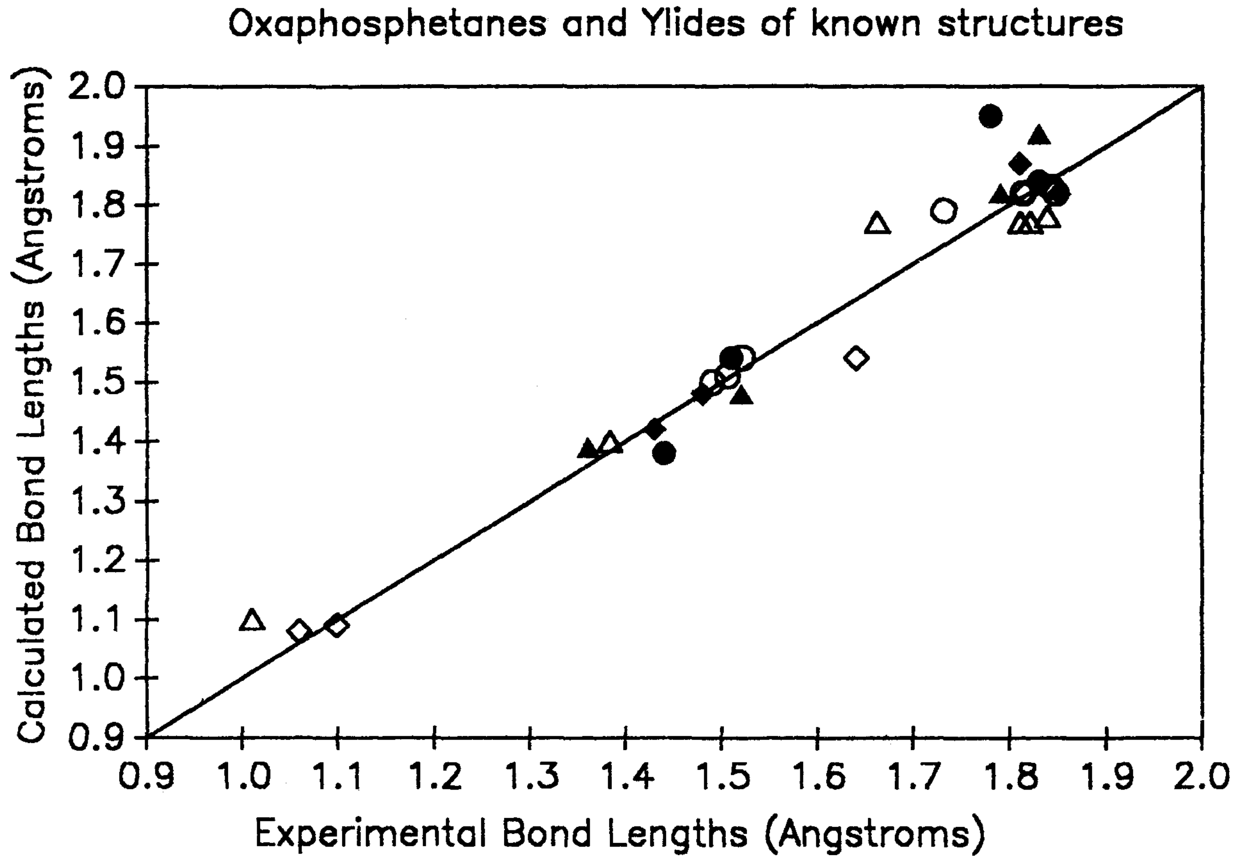


FIGURE 3 Correlation of bond lengths between the calculated values using the MNDO-PM3 method and the experimental values of the oxaphosphetanes and ylides of known structures: ● = *3*, ▲ = *4*, ◆ = *5*, ○ = *6*, △ = *7*, ◇ = *8*. (Other bond length values, besides those shown in Tables 1 and 2, have been included for correlation purposes.)

good bond angle agreement was found between the two methods and no major discrepancies were noticed.

In our first attempt to locate transition states or intermediates of the "mythical Wittig reaction," we carried out a reaction coordinate analysis that involved the C–C bond distance as a variable; the results of this analysis are shown in Figure 5. Analysis of the curve indicates a transition state located at a C–C bond distance of 2.2 Å corresponding to an energy of activation of 9 kcal/mole. In a separate attempt we used the SADDLE routine to locate the transition state and, in this case, the C–C bond distance was found to be 2.07 Å and the energy of activation to be 9.2 kcal/mole. These two results are in general agreement with the previous ab initio results, which computed a C–C bond distance of 2.08 Å and an energy of activation of 5.2 kcal/mole. The use of the unrestricted Hartree–Fock hamiltonian or the configuration interaction method (C.I. = 3 × 3) did not have any effect on our calculations for the transition state; thus, not unexpectedly, any diradical character may be ruled out in this particular case. The transition state found by use of the SADDLE routine is perhaps more self-consistent since no assumptions are made as to the

TABLE 1 Structural Parameters of the Oxaphosphetane Rings of Known Structures: Experimental and Calculated Values Using the MNDO-PM3 Method

Compound	dP–O	dP–C	dC–C	dO–C	<OPC	<PCC	<CCO
3 (exptl)	1.83	1.78	1.51	1.44	75.5	88.1	100.5
3 (calc.)	1.84	1.95	1.54	1.38	72.2	89.0	99.6
4 (exptl.)	1.79	1.83	1.52	1.36	71.6	—	—
4 (calc.)	1.82	1.92	1.48	1.39	70.6	91.9	97.8
5 (exptl.)	1.85	1.81	1.48	1.43	—	—	—
5 (calc.)	1.82	1.87	1.48	1.42	71.4	94.4	95.8

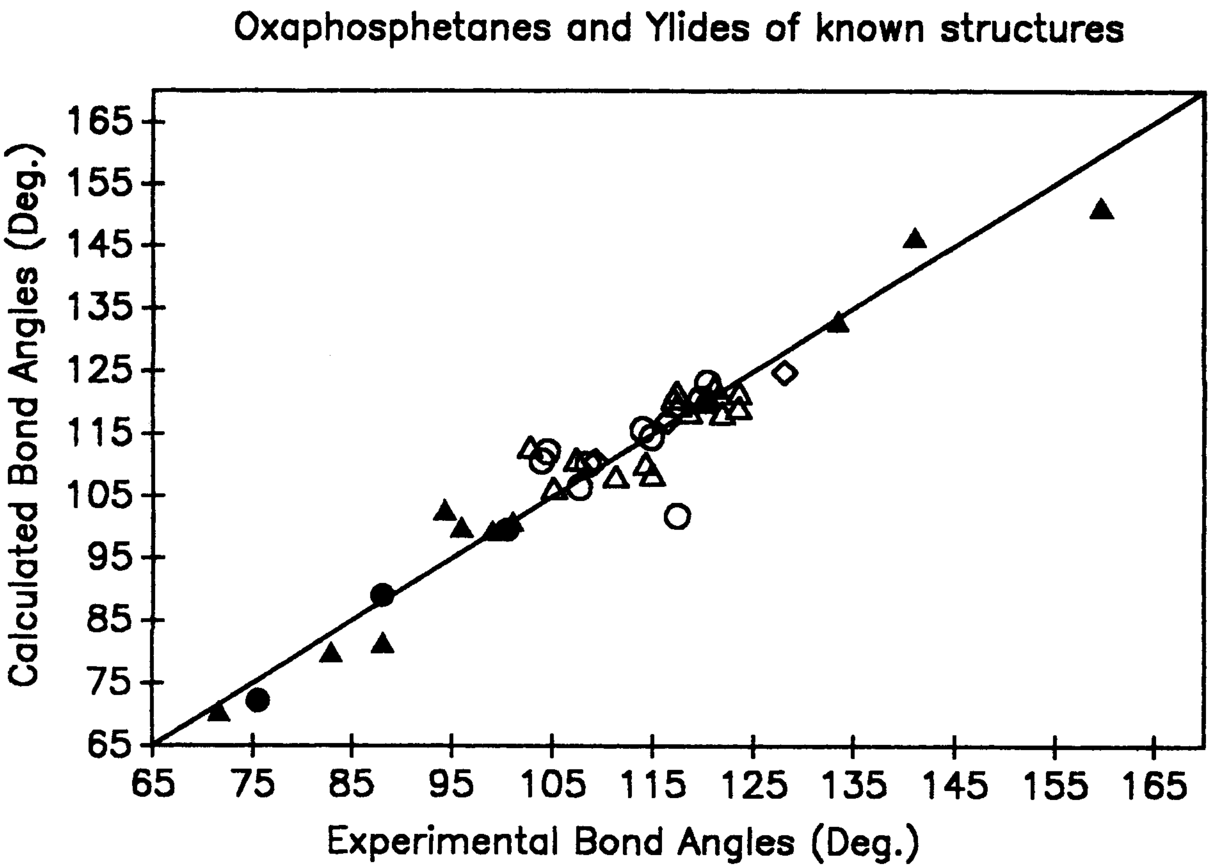


FIGURE 4 Correlation of bond angles between the calculated values using the MNDO-PM3 method and the experimental values of the oxaphosphetanes and ylides of known structures: ● = *3*, ▲ = *4*, ◆ = *5*, ○ = *6*, △ = *7*, ◇ = *8*. (Other bond angle values, besides those shown in Tables 1 and 2, have been included for correlation purposes.)

TABLE 2 Structural Parameters of the Ylides of Known Structures: Experimental and Calculated Values Using the MNDO-PM3 Method

Compound	dP–C$_{\text{av}}$	dP=C	dC–R$_{\text{av}}$	<C–P=C$_{\text{av}}$	<P=C–R$_{\text{av}}$
6 (exptl)	1.83	1.66	0.93	113.5	118.8
6 (calc.)	1.77	1.77	1.10	109.1	120.8
7 (exptl.)	1.83	1.73	1.50	111.2	120.1
7 (calc.)	1.82	1.79	1.51	106.2	122.1
8 (exptl.)	1.64	1.81	1.06	116.5	128.0
8 (calc.)	1.54	1.82	1.08	117.1	124.8

TABLE 3 Structural Features of the Mythical Oxaphosphetane (O-Axial Pseudorotamer): ab initio and MNDO-PM3 Calculated Geometries

Method	dP–O	dP–C	dC–C	dO–C	dP–Hax	dP–Heq	<OPC	<PCC	<CCO	<CPO	<HaxPC	<HeqPC	<HeqPCC
4-31G*	1.757	1.843	1.533	1.399	1.438	1.389	75.9	89.0	98.0	97.1	97.4	123.4	83.0
MNDO-PM3	1.83	1.90	1.52	1.40	1.26	1.24	73.3	90.0	99.5	97.2	92.6	123.6	85.5

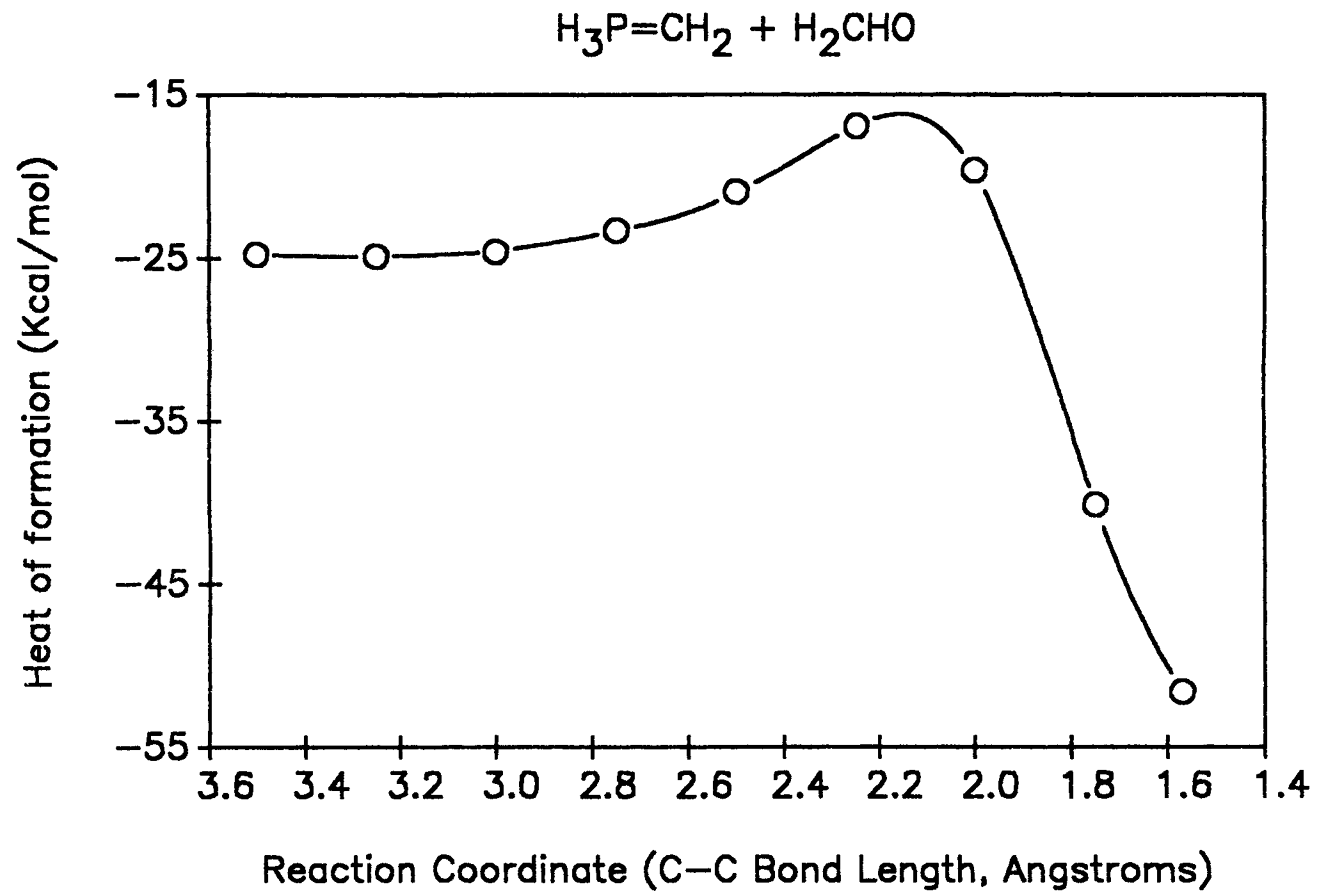


FIGURE 5 MNDO-PM3 energy profile of the mythical Wittig half-reaction.

geometry of the transition state or of the mechanism of the reaction that leads to the transition state [14]. In either case, the results are essentially the same for the reaction coordinate.

The energetics of the Wittig half-reaction at the different levels of theory are compared in Table 4. As reported in the references cited above, the MNDO method yields a poor correlation for the energies of activation and the enthalpy of this half-reaction when compared to the 4-31G* ab initio level of theory, whereas the MNDO-PM3 method gives results that are comparable to those of the ab initio computations. Therefore, it is expected that the MNDO-PM3 method is capable of reproducing the energy profiles of reaction coordinate analysis with an accuracy comparable to that of ab initio methods, whereas the same analysis using the MNDO hamiltonian may give a completely different result. Furthermore, a large discrepancy between the MNDO and the MNDO-PM3 methods was noticed in the heats of formation of the ylide (77.45 versus 11.11 kcal/mole respectively), a difference that might account for the energetics discrepancies previously mentioned using the different levels of theory. These energy differences are not unexpected since we have already pointed out the lack of accuracy of the MNDO methods in the treatment of the hypervalent species involved in this reaction.

Figure 6 and Table 5 show the geometrical correlation (bond length and angles) between the calculated transition state using the MNDO-PM3 semiempirical method with the SADDLE routine and the transition state computed using the 4-31G* ab initio level of theory. An excellent correlation is

TABLE 4 Energetics Comparison of the Wittig Half-Reaction at Different Levels of Theory (All energies are given in Kcal/mole)

	MNDO	MNDO-PM3	4-31G*
Reactants:			
$H_3P{=}CH_2$	77.45	11.11	
$H_2C{=}O$	−32.89	−34.08	
Transition State[a]	61.89	−13.61	
Enthalpies of the reaction, ΔH_r[b]	−11.73	−28.64	−31.9
Enthalpies of activation, $\Delta H^{\neq}$[c]	17.3	9.2	5.2

[a] Transition state found using the SADDLE routine.
[b] Enthalpy of mythical Wittig half-reaction.
[c] Enthalpy of activation of the mythical half-reaction.

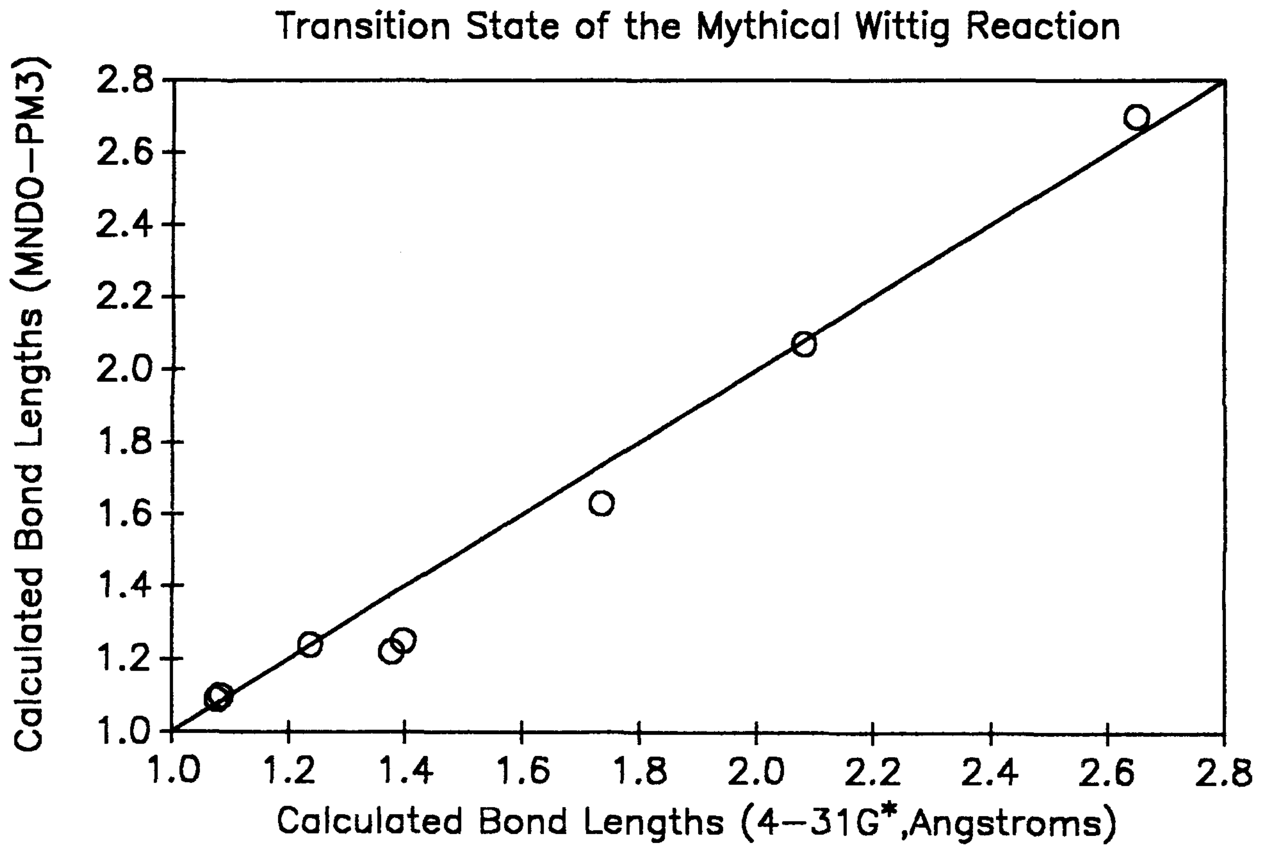


FIGURE 6 Correlation of bond lengths between the calculated values using the MNDO-PM3 method and the calculated values using the 4-31G* ab initio level of theory of the transition state of the mythical Wittig half-reaction.

found for most of the geometrical parameters between the two methods; however, as in the case of the oxaphosphetane, the MNDO-PM3 method underestimates the P–H bond length. As the P–H bond length does not participate in the bond forming-breaking processes that lead to the transition state (see the bond order discussion below), the other geometrical parameters that are involved, such as the P–O bond length and the C–C bond length, are not affected by the differences in the P–H bond lengths. This seems to be the only discrepancy between the results of the MNDO-PM3 method and the ab initio results.

Figure 7 shows the geometrical structure of the transition state calculated using the MNDO-PM3 method. The P–C–C–O dihedral angle is 0.4° indicating that the atoms involved in the bond forming-breaking processes in the transition state lie in a plane for this mythical Wittig half-reaction. In the past, the issue of synchronousness-asynchronousness of a reaction has been addressed by the geometrical analysis of the transition state such as the one presented in Figure 7. In this case, the forming C–C and P–O bond lengths are 2.07 Å and 2.70 Å, respectively, which could in principle be indicative of a synchronous process, if we compared these values with their analogous values in the oxaphosphetane stage: 1.52 Å and 1.83 Å. However, it has been pointed out by Moyano et al. [30, 31] that the use of localized molecular orbitals (LMOs) can yield a more accurate picture of the movement of the electrons throughout a reaction pathway. Likewise, the use of bond orders [29] might be more helpful in developing criteria to determine the bond strengths than the simple examination of bond lengths; i.e., the determination of the importance

TABLE 5 Structural Features of the Transition State of the Mythical Wittig Half-Reaction: ab initio and MNDO-PM3 Calculated Geometries

Method	dP–O	dP–C	dC–C	dO–C	dP-Hax	dP-Heq	<OPC	<PCC	<CCO	<CPO	<HaxPC	<HeqPC	<HeqPCC
4-31G*	2.649	1.736	2.079	1.239	1.398	1.379	73.9	93.9	108.4	83.8	119.4	115.7	60.0
MNDO-PM3	2.70	1.63	2.07	1.24	1.25	1.22	70.9	100.7	104.0	84.4	112.8	115.7	61.8

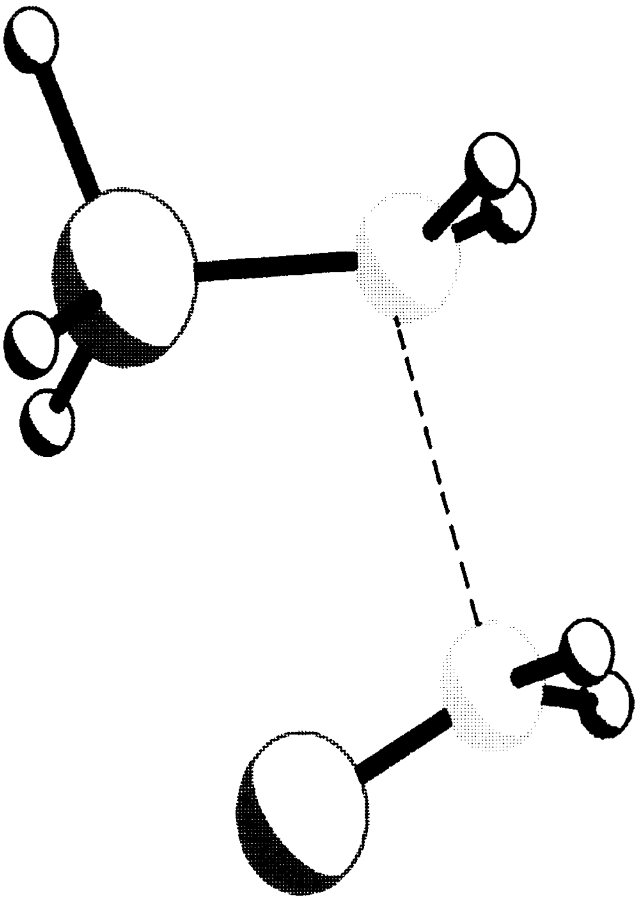


FIGURE 7 Transition state found using the SADDLE routine, calculated by the use of the MNDO-PM3 hamiltonian. The structure shows a partially formed C–C bond, whereas the interaction between phosphorus and oxygen atoms is only electrostatic in nature.

of bonding in cases where the bond distances are substantially larger than their normal values (such as in the case of transition states) might be completely subjective when the bond distances between two atoms are examined, whereas the bond order will be indicative of the bond strength between those two atoms. Table 6 shows the bond orders of the atom pairs involved in the bond forming-breaking processes. (The P–H bond orders have been included to point out the fact that these bond orders do not change during the reaction, indicating that they do not participate in the bond forming-breaking processes. Thus, the miscalculation of the P–H bond lengths by the MNDO-PM3 method should not affect the analysis of the overall process.) These bond order results indicate that, as the P–C and C=O bond strengths are reduced as the reaction proceeds, the C–C bond strength increases, the bond being about 40% formed in the transition state; by contrast to the geometrical analysis, the bond order analysis clearly indicates that C–C bond formation runs ahead of P–O bond formation.

TABLE 6 Bond Orders of Relevant Atom Pairs throughout the Mythical Wittig Half-Reaction

	Reactants: $H_3P{=}CH_2 + H_2C{=}O$	*Transition State*	*Product: Oxaphosphetane*
$P{-}C_1$	1.17	0.98	0.70
$C_1{-}C_2$	—	0.36	0.98
C–O	1.96	1.54	1.00
O–P	—	0.02	0.52
P-Hax	0.81	0.84	0.80
P-Heq	0.80	0.84	0.80

The asynchronousness of the reaction is confirmed by analyzing the energy correlation diagram of the localized molecular orbitals (Figure 8). The movement of the electrons during the mythical Wittig half-reaction may be described by the changes in the LMOs throughout the reaction as follows: the high energy π P–C bond orbital is transformed into a multi-centered mP–C–C–O bond orbital in the transition state, which in turn is transformed into the σ C–C bond orbital in the four-membered ring oxaphosphetane. Meanwhile, the π C–O bond orbital increases in energy, as a consequence of its participation in the transition state, but eventually gets transformed into the σ P–O bond orbital at the oxaphosphetane stage. This description is in agreement with the bond order findings mentioned previously, where the C–C bond formation is more evolved in the transition stage than the P–O bond formation; for that matter, no P–O bonding is involved in the transition state. Most of the transitions from reactants to the transition state are rather smooth (small energy changes are associated with them) representing a noticeable change in the transformation of the π P–C bond orbital into a multi-centered mP–C–C–O bond orbital. On the other hand, in the step from the transition state to product drastic changes in energy and orbital symmetries are observed; i.e., the π C–O bond orbital gets transformed into the σ C–C bond orbital, while the π P–O bond orbital is transformed into the σ P–O bond orbital. The changes in the LMOs of the mythical Wittig half-reaction could also be described with the aid of the scheme provided by Moyano et al. [30]: The LMOs associated with the oxygen atom (π C–O, lσO and lπO) will tend to destabilize the transition state, since in the transition state the LMOs are higher in energy than in the reactants and products. By contrast, the orbitals associated with the phosphorus atom (π P–C and σ P–C) will adapt to the geometry and hybridization changes throughout the reaction path. No major stabilizing LMOs of the *transition state seem* to be present in this mythical Wittig half-reaction. Most of the stabilizing LMOs (σCH and σPH) provide only little stabilization.

In accord with all the data shown above, the mythical Wittig half-reaction is best described as a

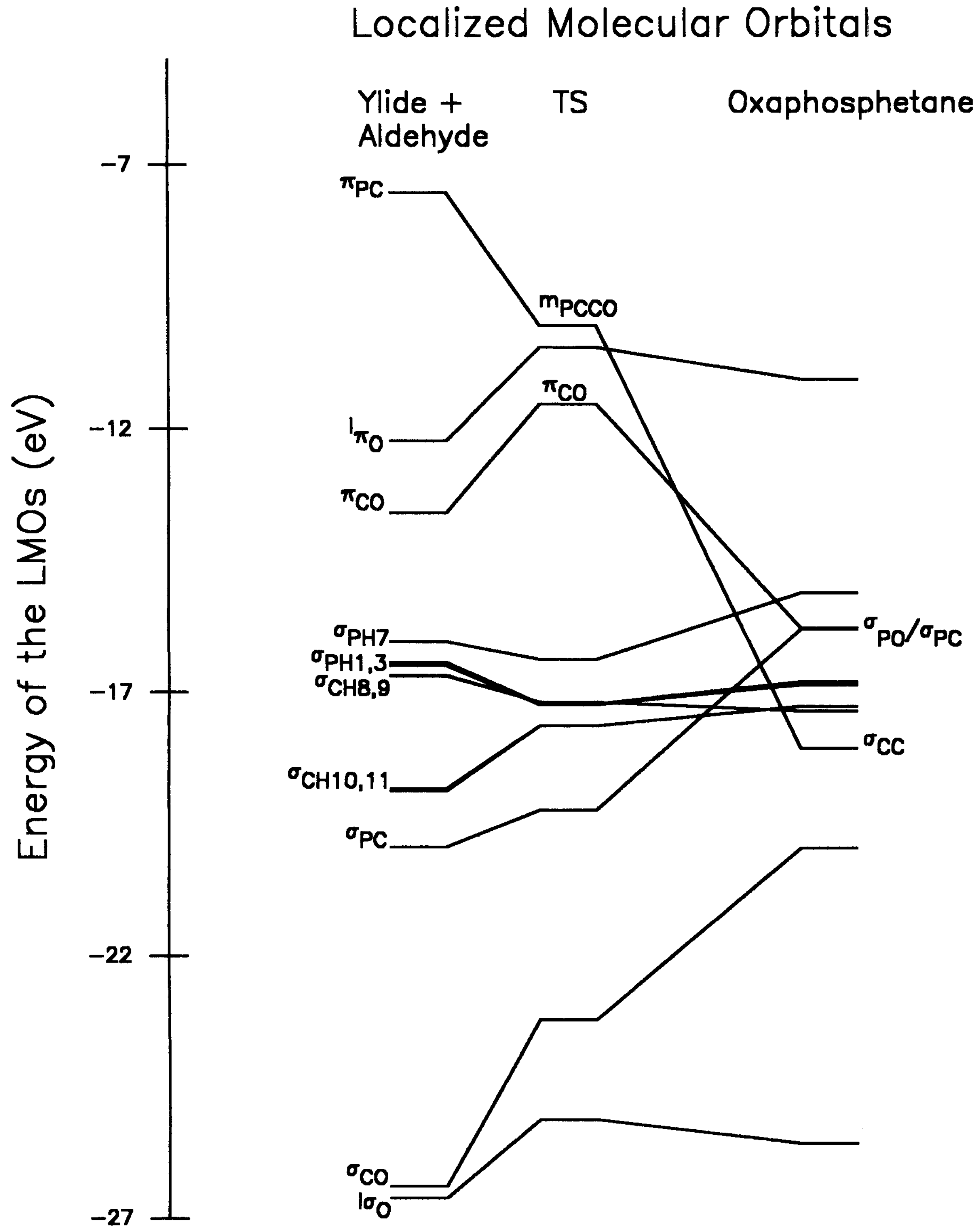


FIGURE 8 Correlation diagram of the localized molecular orbitals (LMOs) of the mythical Wittig half-reaction. The orbitals have been labeled with the following criteria: $l\sigma$ and $l\pi$ refer to the localized monocentric orbitals, σ and π refer to bicentric localized orbitals and the multicentered P–C–C–O localized orbital was designated mPCCO.

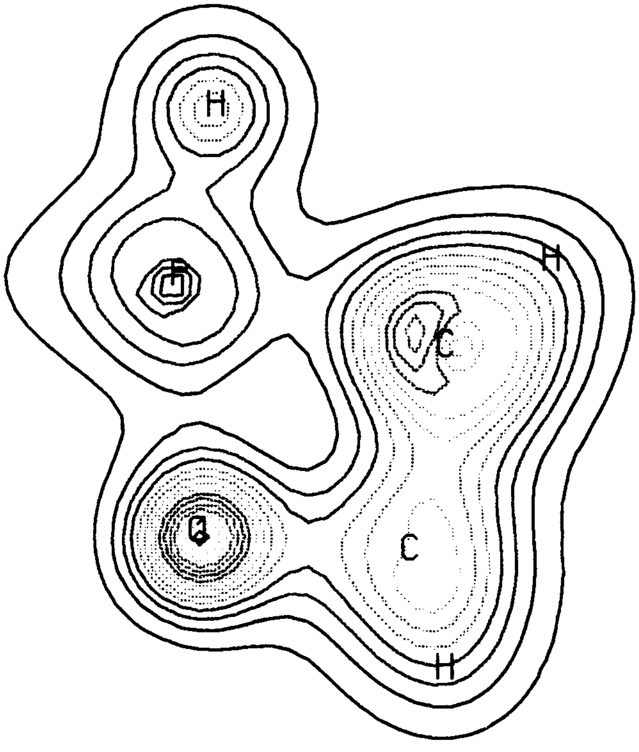


FIGURE 9 Electron density plot of the P–C–C–O plane of the transition state of the mythical Wittig half-reaction. Contour levels are at 0.00, 0.75, 1.00, 1.50, 1.75, 2.25, 2.50, 3.00, 3.25 and 3.75.

very asynchronous (borderline two step) cycloaddition with a planar geometry in the transition state, composed of a multi-centered mP–C–C–O bonding orbital and having the phosphorus and the oxygen atoms sharing a strong charge interaction. This description is represented by Figure 9, which depicts the electron distribution in the transition state, wherein most of the bonding electron density is encountered in the P–C–C–O molecular portion, with no P–O electron bonding density being evident.

SUMMARY AND CONCLUSIONS

We have shown that the MNDO-PM3 semiempirical molecular orbital method is capable of yielding calculated structures of oxaphosphetanes and ylides that are comparable with the experimentally known structures.

We found that the MNDO-PM3 method reproduces the geometrical and thermodynamic parameters of the "mythical Wittig half-reaction", previously calculated using a more elaborate and costly ab initio molecular orbital approach. In addition, using the SADDLE routine, we were able to find a transition state for this half reaction. This transition state resembles geometrically the transition state found using the ab initio approach (4-31G* level). The energy of activation was calculated to be 9.2 kcal/mole, which is comparable with the ab initio result of 5.2 kcal/mole.

According to our calculations, and in general agreement with findings of Volatron and Eisenstein [11], the mythical Wittig reaction would be expected to proceed through a planar transition state for the cycloaddition of the ylide and the aldehyde in a process that superficially seems to be a synchronous one; however, an analysis of the evolution of the bond orders and the localized molecular orbitals throughout the reaction indicates that the P–O bond has not been formed in the transition state, whereas the C–C bond is about 40% formed. In this regard our findings differ from the Volatron and Eisenstein interpretation: they advocated a symmetry controlled synchronous *cycloaddition* by a geometrical examination of the transition state of the mythical Wittig half-reaction, whereas our analysis indicates that the same geometry could be classified as a symmetry-forbidden (F) nonradical (N) process according to the scheme outlined by Yamaguchi et al. [33] and in which a strong ionic character is present in the transition state [34]. A similar description results from computations of the Wittig reactions of $H_3P{=}CHCH_3$ and $(C_6H_5)_3P{=}CHCH_3$ with H_3CCHO, which is inconsistent with the Vedejs geometry, cited above. (This study is presented in detail in another paper that also provides arguments against the Schlosser geometry and mechanism.) The transition state of the step that yields the oxaphosphetane is planar and the initial atomic charge distribution is essentially preserved in the reaction. Other possible intermediates, i.e. anti-betaines [27], radical betaines, and spin paired diradicals [17–19] were found to be higher in energy than the transition state found for the cycloaddition. This result is not surprising since no stabilizing substituents are present in this model reaction. Also, no consideration is given to the presence of solvents that are known to exert a significant effect in most Wittig reactions.

We are in the process of evaluating more realistic systems (i.e., alkyl, vinyl, and aryl substituents present on the phosphorus atom and on the ylidic carbon) that are present in real Wittig reactions. Modeling of the Wittig reaction at the ab initio level of theory in such systems is prohibitive in time and expense with present computational resources. We have shown that a reasonable agreement is found between the use of the semiempirical MNDO-PM3 method and the previous ab initio work in modeling the mythical Wittig reaction. Therefore, for "normal" Wittig reactions (total number of atoms 60 or higher), the use of the MNDO-PM3 semiempirical method is not only the most feasible choice for modeling at the present time, but also one for which good comparison to experiment and rigorous theory may reasonably be expected.

ACKNOWLEDGMENT

This work was supported in part by the National Science Foundation (CHE 8712389). Also, the University of Massachusetts Computer Services made a generous grant of computer time to enable part of this work.

REFERENCES AND NOTES

[1] Part 1, F. Marí, P. M. Lahti, W. E. McEwen, *Heteroatom Chem.*, *1*, 1990, 255.

[2] For an extensive review of the subject see B. Maryanoff, A. E. Reitz, *Chem. Rev.*, *89*, 1989, 863.

[3] An exception to this statement is seen to be the case where R^1 = phenyl and vinyl, and the dibenzophosphole entity is involved in the Wittig reaction (E. Vedejs, T. J. Fleck, *J. Amer. Chem. Soc.*, *111*, 1989, 5861); however, in this case, as it is pointed out by the authors, the possible key factors that are responsible for the regioselectivity of the Wittig reaction, such as the phosphorus hybrydization and the oxaphosphetane pseudorotation, are very different as compared with "normal" Wittig reactions where the substituents on the phosphorus atoms are phenyls.

[4] a) M. Schlosser, B. Schaub, *J. Am. Chem. Soc.*, *104*, 1982, 3989. b) M. Schlosser, R. Oi, B. Schaub, *Phosphorus and Sulphur*, *18*, 1983, 171.

[5] E. Vedejs, C. F. Marth, *J. Am. Chem. Soc.*, *110*, 1988, 3948.

[6] B. E. Maryanoff, A. B. Reitz, M. S. Mutter, M. S. Inners, R. R. Almond, H. R. Whittle, R. R. Olofson, *J. Am. Chem. Soc.*, *108*, 1986, 7664.

[7] C. Trindle, J. T. Hwang, F. A. Carey, *J. Org. Chem.*, *38*, 1973, 2664.

[8] a) H. J. Bestmann, *Pure & Appl. Chem.*, *52*, 1980, 771. b) H. J. Bestmann, O. Vostrowsky, *Top. Curr. Chem.*, *109*, 1983, 85.

[9] H. J. Bestmann, J. Chandrasekhar, W. G. Downey, P. R. Schleyer, *Chem. Comm.*, 1980, 978.

[10] R. Höller, H. Lischka, *J. Am. Chem. Soc.*, *102*, 1980, 4632.

[11] F. Volatron, O. Eisenstein, *J. Am. Chem. Soc.*, *109*, 1987, 1.

[12] J. J. P. Stewart, *J. Compt. Chem.*, *10*, 1989, 209.

[13] J. J. P. Stewart, *J. Compt. Chem.*, *10*, 1989, 221.

[14] J. J. P. Stewart, M. J. S. Dewar, *J. Chem. Soc. Faraday Trans. 2*, *3*, 1984, 227.

[15] M. J. S. Dewar, J. J. P. Stewart, *Quant. Chem. Exchange*, Program 506 (1987).

[16] K. Steliou, University of Montreal, Quebec, Canada.

[17] W. E. McEwen, B. D. Beaver, J. V. Cooney, *Phosphorus and Sulfur*, *25*, 1985, 255.

[18] W. J. Ward, Jr., W. E. McEwen, *Phosphorus and Sulphur*, *41*, 1989, 393.

[19] W. J. Ward, Jr., W. E. McEwen, *J. Org. Chem.*, *55*, 1990, 493.

[20] L. Salem, C. Rowland, *Angew. Chem., Int. Ed. Engl.*, *11*, 1972, 92.

[21] M. Ul-Haque, C. N. Caughlan, F. Ramirez, J. F. Pilot, J. P. Smith, *J. Am. Chem. Soc.*, *93*, 1971, 5229.

[22] H. E. Aly, J. H. Barlow, D. R. Russel, D. J. Smith, M. Swindles, S. Trippett, *J. Chem. Soc., Chem. Commun.*, 1976, 449.

[23] H. J. Bestmann, K. Roth, E. Wilhelm, R. Böhme, H. Burzlaff, *Angew. Chem., Int. Ed. Eng.*, 1979, 876.

[24] J. C. J. Bart, *J. Chem. Soc.* (*B*), 1969, 350.

[25] H. Schmidbaur, A. Schier, C. Frazão, G. Müller, *J. Amer. Chem. Soc.*, *108*, 1986, 976.

[26] E. A. V. Ebsworth, T. E. Fraser, D. W. H. Rankin, *Chem. Ber.*, *110*, 1977, 3494.

[27] W. P. Schneider, *Chem. Comm.*, 1969, 785.

[28] P. G. Perkins, J. J. P. Stewart, *J. Chem. Soc., Faraday Trans. II*, *76*, 1980, 520.

[29] D. R. Anstrong, P. G. Perkins, J. J. P. Stewart, *J. Chem. Soc., Dalton Trans.*, 1973, 838.

[30] A. Moyano, M. A. Pericàs, F. Serratosa, E. Valentí, *J. Org. Chem.*, *52*, 1987, 5532.

[31] A. Moyano, M. A. Pericàs, E. Valenti, *J. Org. Chem.*, *54*, 1989, 573.

[32] J. J. P. Stewart, *Quant. Chem. Exchange*, Program 492, 1st ed.

[33] K. Yamaguchi, T. Fueno, H. Fukutome, *Chem. Phys. Lett.*, *22*, 1973, 461.

[34] In a study of the "reaction" between $H_3P{=}CH_2$ and $H_2C{=}O$ that is similar to ours, H. S. Rzepa (*J. Chem. Soc., Perkin Trans II*, 1989, 2115) has reported a planar, symmetrical saddle point for this half reaction at the MNDO-PM3 level, and has described the process as an allowed cycloaddition. "The 'allowed' character of the . . . reaction is attributed to contributions from the P–H bonds, and not to asymmetry in the reactant orbitals or to ionic characters in the wavefunction." This is inconsistent with our analysis of the evolution of the bond orders and localized molecular orbitals throughout the reaction (see Table 6 and Figure 8).