

RF Plasma Promoted Di- π -methane Rearrangement of 3-Phenylpropene

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3-Phenylpropene reacted in an RF plasma to produce phenylcyclopropane and other products. 3-Phenyl-2-deuteriopropene produced 1-phenyl-1-deuteriocyclopropane. The kinetics of the plasma reaction for 3-phenylpropene, indene, and phenylcyclopropane were investigated.

The plasma generated by an electrical discharge provides an unusual gaseous, but ionic medium for reactions.¹ The free electrons present in the plasma are responsible for the chemical reactions which take place, in the sense that they are accelerated by the applied electrical field, impact on molecules, and in this way activate the molecules for reaction. Studies of this electron impact chemistry with complex molecules have been relatively rare. It has been shown, though, that some unusual reactions occur and in a few cases the yields of a single product are high. Most studies have employed radio frequency (RF) discharges and in these systems the pressure, power, and the temperature of the unactivated molecules are relatively low. The system is usually set up so that the compound of interest is distilled through a plasma zone, with a residence time in the zone on the order of a second.

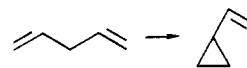
In these RF studies both aromatic compounds and alkenes have received attention. In general it has been found that if other reaction modes are available in other parts of the molecule, an aromatic ring will remain unaffected.^{1,2} Aromatic rings, however, are susceptible to substitution reactions. For example, cyanation³ and hydrogen-deuterium exchange⁴ take place. Specifically toluene with cyanogen gives *o,m,p*-cyanotoluenes plus cyanobenzene. Toluene-*d*₃ in the presence of hydrogen produces toluene-*d*₇, *d*₆, etc. as well as benzene-*d*₅.

The plasma chemistry of alkenes is similar in that some substitution reactions are known. Not unexpectedly, other reaction modes, fragmentation and isomerization also seem common. For example, *cis*- and *trans*-stilbene interconvert and cyclize to phenanthrene.⁵ *cis*-2-Butene isomerizes cleanly to *trans*-2-butene and 1-butene under low-power or high-pressure conditions. It fragments to C₂ and C₃ products under high power or low-pressure conditions, where the electron energy density is higher.⁶

In studies from this laboratory we have made a practice of controlling the flow rate (*r*) and the power (*P*) and we have tried to understand the changes in products as well as the kinetics of reactant disappearance when these parameters are varied. As indicated above for 2-butene, the composition of the products can be affected substantially by conditions. In another example, the relative yield of benzene from toluene and hydrogen goes up as the power is increased.³ In other cases a similar yield/*P* dependence is not observed.⁷ In the few examples studied it has commonly been found that the rate of disappearance of reactant molecules can be described by a linear relationship

between log (*A/A*₀) (amount recovered/amount passed) and *Pr*⁻¹.⁸ Two important factors leading to this relationship are the electron energies and the residence time.

In the present case, we set out to discover and study a reaction that would clearly mimic organic photochemistry. Such mimics are few in number, but do exist. For example, the *cis*-2-butene isomerization to *trans*-2- and 1-butene takes place photolytically at 200 nm as well as by RF. We were, however, attracted by a more complicated isomerization—one relatively inaccessible to free radical routes involving fragmentation and recombination and one which would in a sense provide a signature indicating excited-state chemistry was involved. For these reasons, the di- π -methane isomerization rose to the surface of our considerations. This is a unique reaction exemplified by the prototypical case of 1,4-pentadiene photolysis forming, in the gas phase, vinyl cyclopropane.⁹ Many examples of this kind of rearrangement reaction exist for the solution phase.^{10,11}



In a preliminary communication¹² we have revealed that 1,3-pentadiene produces vinylcyclopropane and 3-phenylpropene gives phenylcyclopropane. In the present paper a detailed study of the latter reaction is described.

Results and Discussion

The inductively coupled plasma apparatus used in the present study was very similar to that described previously.⁴ The reactant was distilled through the discharge zone produced by an RF generator at 13.56 MHz. Products and unreacted starting materials were collected in a liquid nitrogen cold trap and were analyzed by GC. The major products were isolated by preparative GC and identified by spectral means by comparison with authentic samples; minor products were identified by GC-MS. Their yields were determined by GC with an internal standard.

Two reactants were investigated. 1,4-Pentadiene (1) produced vinylcyclopropane (2), cyclopentene (3), and cyclopentadiene (4). At 40-W with a flow rate (*r*) of 3.5 mmol min⁻¹ the yields based on the amount of 1 passed through the reactor were 2 (5%), 3 (21%), and 4 (18%). Major attention was given to the reaction of 3-phenylpropene (5). A major product was phenylcyclopropane 6. In addition, smaller variable amounts of benzene, toluene,

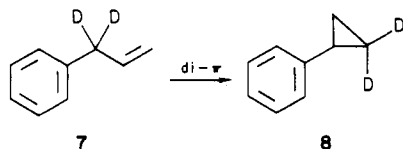
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styrene, cumene, propylbenzene, β -methylstyrene, 3-phenylpropene, indan, and indene were also obtained.

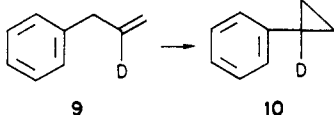
Of most importance to us was the mechanism of formation of phenylcyclopropane by an apparent di- π -methane reaction. We sought to examine the mechanistic question with deuterium-labeled substrates. 3-Phenyl-



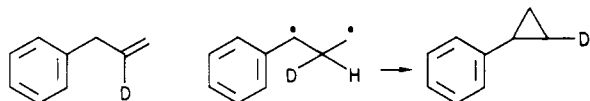
3,3-dideuteriopropene (7) was prepared and reacted as usual. In this case a di- π -methane process would produce 8. However, the experimental result was equivocal because the product contained both phenylcyclopropane- d_1 (21%) and d_2 (79%). This precluded a useful NMR analysis of the position(s) of the deuterium.

It was reasoned that the phenylcyclopropane- d_1 might come from H/D exchange reactions similar to those observed for toluene. The location of the deuteriums at the benzylic/allylic position of the starting material would make that possibility especially facile. Following this reasoning, 3-phenyl-2-deuteriopropene (9) was prepared in which the label was at a nonlabile position. This compound was produced by D_2O quench of 2-lithio-3-phenylpropene produced by adding *n*-butyllithium in the mixture of hexane and 1-phenyl-2-propanone [(2,4,6-trisopropylphenyl)sulfonyl]hydrazone. NMR and MS analysis indicated the product 9 contained >95% deuterium at position 2.

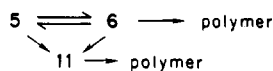
Reaction of 9 gave phenylcyclopropane after GC collection, which gave a mass spectrum indicating that it was monodeuterated, i.e., the peak intensities at m/e 118 (76) and 117 (100) for phenylcyclopropane were displaced to 119 (81) and 118 (100) in the product 10. The position of the deuterium in 10 was demonstrated by deuterium NMR. The 2H NMR spectrum, 1H -decoupled, showed only one peak at δ 1.91. (At higher sensitivity the natural abundance deuteriums could be observed.)



This result suggests a rearrangement of the carbon skeleton which is consistent with the di- π -mechanism, a formal $\sigma_2 + \pi_2$ cycloaddition. The result rules out the very reasonable possibility that a 1,2-hydrogen shift was involved.



It was of interest to unravel a bit more of the kinetic story for the reaction of 5. In order to do so, it was necessary to study the plasma reactions of the products cyclopropylbenzene (6) and also indene (11). When submitted to the same reaction conditions, 6 provided 5 and 11 as well as polymer. Indene gave only polymer and a trace of indan (0.1–2.0%). There were no volatile products. These results then demonstrate:



The yields of polymer were substantial when 5 or 6 was reacted so it seems likely that these two compounds can

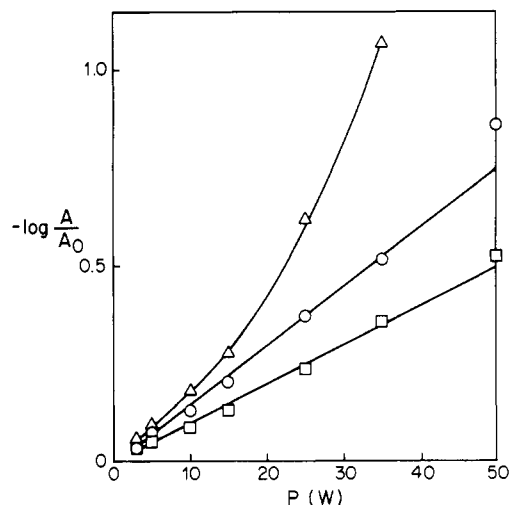


Figure 1. Reaction rate as power is varied. (□) Cyclopropylbenzene, (O) allylbenzene, (Δ) indene.

Table I. Conversion of 5 as P Is Varied^a

P, W	$10^2 \left(\frac{A_0 - A}{A_0} \right)^b$	P, W	$10^2 \left(\frac{A_0 - A}{A_0} \right)^b$
3	8.4 ± 0.8	25	57.4 ± 0.5
5	15.1 ± 0.6	35	69.5 ± 0.2
10	25.6 ± 0.1	50	86.3 ± 0.4
15	37.4 ± 0.3		

^a $r = 0.91 \pm 0.04$ mmol min^{-1} . ^b Av of two runs and range of values.

Table II. Conversion of 6 and 11 as P Is Varied^a

P, W	$10^2 \left(\frac{A_0 - A}{A_0} \right)^b$	
	6	11
3	7.4 ± 1.0	12.6 ± 0.5
5	10.9 ± 0.9	18.3 ± 0.1
10	18.1 ± 0.7	33.7 ± 2.0
15	25.8 ± 0.8	46.7 ± 0.4
25	41.9 ± 0.2	75.9 ± 4.5
35	56.2 ± 2.1	89.5 ± 0.3
50	69.8 ± 0.0	100.0 ± 0.0

^a $r_6 = 0.92 \pm 0.06$ mmol/min. $r_{11} = 0.93 \pm 0.10$ mmol/min.

Table III. Conversion of 5 as r Is Varied^a

$r, \text{mmol min}^{-1}$	$10^2 \left(\frac{A_0 - A}{A_0} \right)$	$r, \text{mmol min}^{-1}$	$10^2 \left(\frac{A_0 - A}{A_0} \right)$
2.14	15.8	0.41	67.7
0.91	36.1	0.33	77.0
0.53	57.6	0.28	85.3

^a Power = 15 W.

form polymer without going through 11.

Considerable effort was expended to obtain reliable kinetic data. In Table I are some of the results obtained by using 5 when the flow rate (r) was held constant and the power (P) was varied. In these experiments the pressure is relatively constant. It can be seen that the extent of conversion of 5 went up as the power was increased. This data can be treated by a pseudo-first-order rate law as shown in Figure 1. At conversions less than about 70% the plot is satisfactorily linear. The kinetics of the disappearance of 6 and 11 were also measured (Table II and Figure 1). It can be seen that cyclopropylbenzene conversion increases linearly with P and that cyclopropylbenzene reacts more slowly than 3-phenylpropene. Indene reacts somewhat more rapidly and shows distinctly nonlinear behavior in this plot. The conversion increases

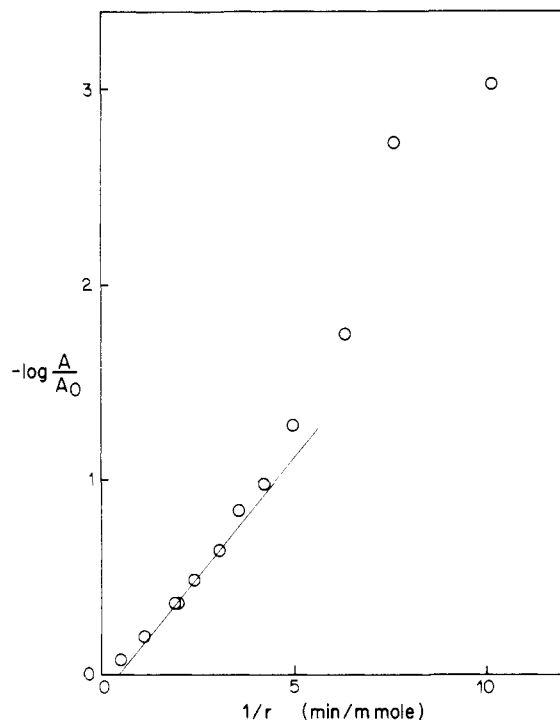


Figure 2. Reaction rate of allylbenzene as flow rate is changed.

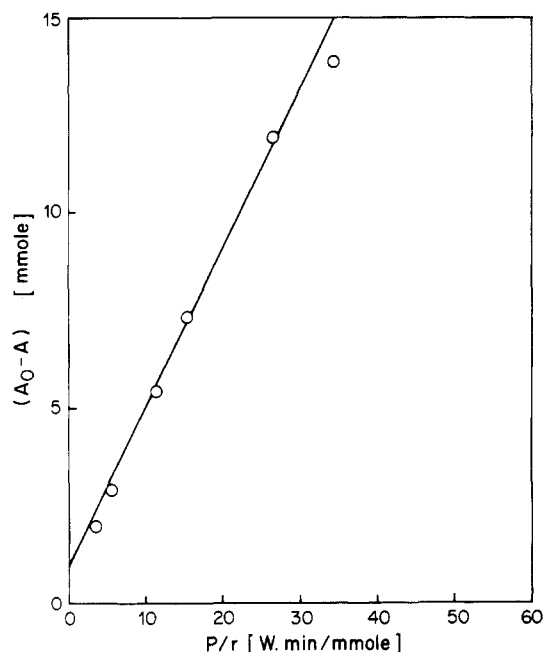


Figure 3. Reaction rate of indene.

unexpectedly as P increases. In a qualitative sense then these data show that, especially at high power, indene will never build up as a product because it polymerizes too rapidly.

In a second set of experiments the flow rate of 5 was varied while P was held constant (Table III). A linear relation between log conversion was observed (Figure 2) at conversions up to about 60%. The behavior of indene was different as shown in Figure 3. For indene all the data for P and r variation could be fit to an apparent "zero-order" rate law, i.e., the amount of indene which reacted was proportional to Pr^{-1} . These results show that rearranging and polymerizing systems have different rate laws. Since a competition between unimolecular rearrangement or fragmentation and polymerization seems a common phenomenon in plasma reactions, this observation could

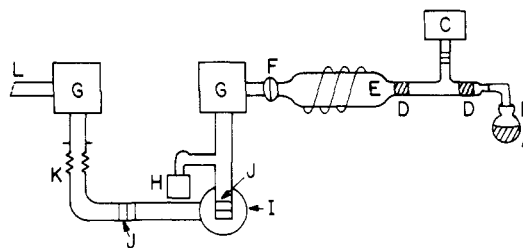


Figure 4. Plasma apparatus.

prove important in understanding and controlling the relative rates of other plasma processes.

Experimental Section

Materials and Apparatus. All chemicals were from commercial sources. They were shown to be pure by GC. Authentic samples of the reaction products were also purchased. The RF power supply was an International Plasma Corp. Model PM 105D. Forward and minimized reverse power were measured with a Bird wattmeter. Tuning was accomplished with a modified Heathkit antenna tuner.

The plasma apparatus shown schematically in Figure 4 was employed. It consisted of a liquid reservoir from which the starting materials were distilled through a Teflon needle valve. The Pyrex reactor tube was 2.5 cm \times 28 cm. The inductance coil was 10 turns of 0.25-in. OD copper tubing. An MKS 254 controller was used for observation of the pressure. The starting compounds were contained in a flask (A) and distilled out through a Teflon needle valve (B). The flow rate was controlled by using the needle valve and always checked by the pressure transducer (C), a Baratron gauge (MKS 222A). Glass wool was placed at the gauge for protection of the gauge. The distilled compound next flowed through the glass reactor (E). After exiting the reactor, gases were directed to a liquid nitrogen cold trap (I) through 0.5-in. OD tubing. Toggle valve (H) (Whitney SS-16S4) allowed release of the vacuum on the trap. The socket on the trap was joined to a ball, which was in turn connected to the stainless steel tubing via a Cajon Ultra-torr fitting (J). Bellows (I) were placed in the line. This, along with the ball-and-socket joints, provided flexibility and allowed rapid changing of the glass trap without breakage. The line itself was 0.5-in. OD stainless steel wherever potentially corrosive chemicals were being encountered. Elsewhere, copper tubing was used. Finally, it is noted that the sections which needed routine cleaning could be easily removed since they were attached with ground glass joints or swagelock fittings.

The flow rate was calculated from the measured time, which was needed to distill out a known weight of compound (approximately 2 g) from the flask.

Analysis. Analysis of the products was carried out with a temperature-programmed GC equipped with a flame-ionization detector. A 3-m, 20% OV-17 on silylated, acid-washed Chromosorb W was used. The products were identified by retention time comparison with authentic samples and in most cases confirmed by gas chromatography-mass spectroscopy. Product and recovered starting material yields were estimated by GC by using an internal standard.

Mass spectrometry was performed by using a Finnigan 4000 GC-MS interfaced to a VG M82L Multispace Data System. For the analysis of deuterium positions in deuterated cyclopropylbenzene, a gas chromatograph with a thermal-conductivity detector was used. The deuterated compound was collected with a liquid nitrogen cold trap.

Reaction of 2-Deuterio-3-phenylpropene (9). Compound 9 was prepared¹³ by D_2O quench of 2-lithio-3-phenylpropene by addition of *n*-butyllithium (in hexane 2 M, 2.0–2.2 equiv.) to phenyl-2-propanone [(2,4,6-triisopropylphenyl)sulfonyl]hydrazone in 10% TMEDA hexane solution at $-78^\circ C$. Compound 9 was purified by extraction with ether, washing with water, and distillation. The mass spectrum, m/e 119 (77.7% relative intensity),

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118 (110), 117 (20), 116 (28), 91 (26), 39 (21), can be compared to that of 3-phenylpropene, *m/e* 118 (80.7), 117 (100), 115 (35), 91 (68), 39 (23). The NMR spectrum of **9**, 3.37, 5.05, 7.22, can be compared to that of 3-phenylpropene δ 3.32, 5.03, 5.68~6.18, 7.71.

Reaction of **9** ($P = 15$ W, $av\ r = 0.8$ mmol/min) was followed by GC collection, NMR, and MS analysis. The ^1H NMR spectrum of the cyclopropylbenzene-*d*₁ was δ 0.69, 0.94, 7.05, and 7.22. The ^2H NMR spectrum had one peak at δ 1.91. These chemical shifts can be compared to those of cyclopropylbenzene δ 0.53, 0.68, 1.64, 6.94, and 7.09. The mass spectrum, *m/e* (relative intensity) 119

(80.8), 118 (100), 117 (21.1), 116 (29.2), 92 (35.5), 91 (37.6), 51 (25.4), 39 (24.7), can be compared to that of cyclopropyl benzene, *m/e* (relative intensity) 118 (79.4), 117 (100), 115 (30.2), 91 (21.2), 39 (29.3).

Acknowledgment. This work was supported by the National Science Foundation.

Registry No. 1, 591-93-5; 5, 300-57-2; 6, 873-49-4; 7, 60604-09-3; 9, 60468-24-8; 10, 35024-14-7; indene, 95-13-6; 2-lithio-3-phenylpropene, 63883-88-5.

Synthesis of (2*R*,3*S*,22*R*,23*R*)- and (2*R*,3*S*,22*S*,23*S*)-2,3,22,23-Tetrahydroxy-*B*-homo-7 α -oxa-5 α -ergostan-7-ones, Two New Brassinolide Analogues

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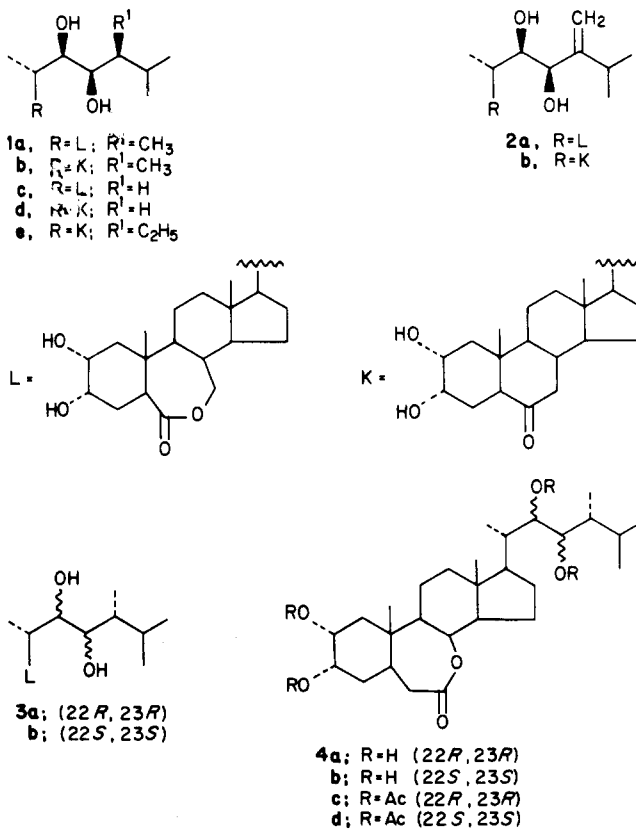
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(2*R*,3*S*,22*R*,23*R*)- and (2*R*,3*S*,22*S*,23*S*)-2,3,22,23-tetrahydroxy-*B*-homo-7 α -oxa-5 α -ergostan-7-ones (**4a** and **4b**) were synthesized starting from the 5 α -ergosta-2,7,22-triene (**7**). Osmilation of the 2,7,22 double bonds of **7** afforded the two hexols **6** which were rearranged by acidic treatment to (2*R*,3*S*,22*R*,23*R*)- and (2*R*,3*S*,22*S*,23*S*)-2,3,22,23-tetrahydroxy-5 α -ergostan-7-ones (**5a** and **5b**) whose structures were determined by chemical methods. Baeyer-Villiger oxidation of the 7-oxo group of **5a** and **5b** afforded **4a** and **4b**, respectively. The triene **7** was obtained in pure form by dehydrosylation of the 3 β -hydroxy-3',5'-dioxo-4'-phenyl-5,8[1',2']-1',2',4'-triazolidino-5 α ,8 α -ergosta-6,22-diene 3-*p*-toluenesulfonate (**8**) and subsequent reduction with lithium dissolved in liquid ammonia of the obtained 3',5'-dioxo-4'-phenyl-5,8[1',2']-1',2',4'-triazolidino-5 α ,8 α -ergosta-2,6,22-triene (**9**).

The past few years have seen an increasing interest in plant growth promoting compounds which led to the discovery of a new class of plant growth steroidal hormones including brassinolide (**1a**)¹⁻⁴ and other closely related steroids such as catasterone (**1b**),²⁻⁵ dolicholide (**2a**),^{6,7} dolichosterone (**2b**),^{6,7} 28-norbrassinolide (**1c**),⁸ brassinone (**1d**),⁸ (2*S*)-24-ethylbrassinone (**1e**),⁸ and typhasterol (2-deoxycasterone).⁹

Syntheses of brassinolide (**1a**), dolicholide (**2a**), and many brassinolide analogues (Chart I) have already been reported by different laboratories.¹⁰⁻²⁵ Structure-activity

Chart I



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(13) Fung, S.; Siddall, J. B. *J. Am. Chem. Soc.* 1980, 102, 6580.

relationships of brassinosteroids with respect to the stereochemistry of the side chain were investigated by using