

Determination of the Minimum-Energy Conformation of Allylbenzene and Its Clusters with Methane, Ethane, Water, and Ammonia

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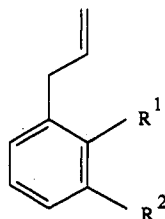
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Supersonic molecular jet laser time-of-flight mass spectroscopy (TOFMS) is employed to determine the minimum-energy conformation of the allyl group with respect to the benzene ring of allylbenzene, 1-allyl-2-methylbenzene, and 1-allyl-3-methylbenzene. The spectra are assigned and conformations are suggested with the aid of molecular orbital-molecular mechanics (MOMM-85) calculations. Based on the experimental and theoretical results, the minimum-energy conformer is found to have $\tau_1(\text{C}_{\text{ortho}}-\text{C}_{\text{ipso}}-\text{C}_\alpha-\text{C}_\beta) = \text{ca. } 90^\circ$ (i.e., the allyl group is essentially perpendicular to the plane of the benzene ring) and $\tau_2(\text{C}_{\text{ipso}}-\text{C}_\alpha-\text{C}_\beta-\text{C}_\gamma) = \pm 120^\circ$ (i.e., the olefin $\text{C}=\text{C}$ bond is eclipsed with the $\text{C}_\alpha-\text{H}_\alpha$ bond). The TOFMS of allylbenzene clustered with methane, ethane, water, and ammonia are also presented. A Lennard-Jones potential energy 6-12-1 atom-atom calculation is used to characterize the structures of these clusters. Experiments and calculations demonstrate that the four different solvent molecules studied can form stable clusters with allylbenzene by coordinating to the π -system of the allyl substituent in addition to that of the aromatic ring.

I. Introduction

Supersonic molecular jet laser spectroscopy has recently been proven to be a remarkably capable technique for the observation and structural characterization of a wide variety of alkyl- and heteroalkyl-substituted benzenes.¹⁻⁷ For example, the minimum-energy conformations of various ethyl-,¹ propyl-,³ butyl-,⁴ and methoxybenzenes^{5,6} and styrenes⁷ have been observed for the first time and their stable conformations have been experimentally determined. In addition, molecular jet laser spectroscopy has been able to characterize potential energy barriers, typically for aromatic methyl rotors, for some of these molecules in both their ground and excited states.^{2,6,8}

In this paper, we focus attention on the effects of a carbon-carbon double bond (an additional π -system) incorporated onto an aromatic ring in terms of the geometry of the minimum-energy conformation(s) of the molecule and on the geometry of various van der Waals clusters. The specific systems studied are allylbenzene (**1**), the allyltoluenes (**2** and **3**), and the van der Waals



- 1, $\text{R}^1 = \text{R}^2 = \text{H}$
 2, $\text{R}^1 = \text{CH}_3$, $\text{R}^2 = \text{H}$
 3, $\text{R}^1 = \text{H}$, $\text{R}^2 = \text{CH}_3$

clusters formed between allylbenzene and methane, ethane, water, and ammonia. Even though the allylbenzene substructure is found in numerous natural products and has value in organic synthetic manipulations, its conformational properties have received little attention.⁹ Indeed, there is a dearth of both experimental and theoretical information regarding the conformational preferences of allylbenzene and its derivatives.

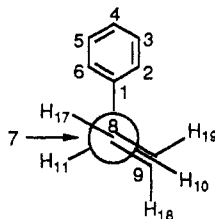
Spectroscopic studies of these systems are obtained through supersonic molecular jet cooling and isolation of the various species in the gas phase and one- and two-color time-of-flight mass

spectroscopy (TOFMS) detection. Mass-selected excitation spectra of isolated molecules and clusters are thus obtained.¹⁰ In order to determine the conformations and cluster geometries associated with the individual mass-selected spectra observed, model calculations of the isolated and clustered species are performed.¹²

Five questions are addressed in this work: (1) Can the stable conformations be isolated and spectroscopically observed for allylbenzene and alkyl-substituted allylbenzenes? (2) What are the minimum-energy conformations of the allyl group in allylbenzenes? (3) What are the configurations of clusters of allyl-

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- (10) (a) The name "one (and two) color time-of-flight mass spectroscopy" is generally employed to describe the following experiment. A sample is irradiated with a laser of energy ν_1 , resulting in the generation of the first excited singlet state ($\text{S}_1 \leftarrow \text{S}_0$). A second photon ν_2 subsequently ionizes those molecules in S_1 ($\text{S}_1 \rightarrow \text{I}^+$). The ions are detected in given mass channels by time-of-flight mass spectroscopy, such that only ion current representing a chosen m/z is recorded. The energy of the ν_1 laser is changed, and a mass-selected excitation spectrum is obtained. (b) In early pioneering work, Smalley and co-workers^{11a,b} and Ito and co-workers^{8b,11c} have reported the fluorescence excitation (FE) spectra and dispersed fluorescence spectra of various aromatic compounds. Because FE results are not mass selected, ambiguity may exist regarding the source of some of the transitions.
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TABLE I: Partial Electronic Charges for Allylbenzene^a


atom ^b	q	atom ^b	q
1 (C)	-0.01	11 (H)	0.059
2 (C)	-0.064	12 (H)	0.058
3 (C)	-0.060	13 (H)	0.057
4 (C)	-0.063	14 (H)	0.056
5 (C)	-0.060	15 (H)	0.057
6 (C)	-0.065	16 (H)	0.062
7 (C)	-0.106	17 (H)	0.059
8 (C)	-0.046	18 (H)	0.057
9 (C)	-0.128	19 (H)	0.055
10 (H)	0.057		

^a From STO-3G calculations using the MOMM-85 derived energy minimum. ^b Other attached atoms, not shown in the diagram, are 2-12, 3-13, 4-14, 5-15, and 6-16.

benzenes with small solvent molecules? (4) Does solvation influence the allylbenzene molecular geometry significantly? (5) Does the π -system of the allyl group influence significantly the solvation of the aromatic ring in substituted benzenes?

II. Experimental Procedures

The supersonic jet time-of-flight mass spectrometer is as described previously.¹³ Expansion into the vacuum chamber is achieved with an R. M. Jordan pulsed valve. In the case of the allylbenzene van der Waals clusters, two-color photoionization spectra are obtained by using two Quanta-Ray Nd:YAG-pumped tunable dye lasers to generate the pump and ionization beams. The energy of the tunable pump beam (0.5–1.0 mJ/pulse) is typically $\sim 37\,500\text{ cm}^{-1}$ while that of the fixed-wavelength ionizing beam (1.0–2.0 mJ/pulse) is $\sim 34\,000\text{ cm}^{-1}$. Under these experimental conditions no one-color spectra, due only to the pump beam, are observed. Complications due to fragmentation of higher order clusters are avoided by careful control of the allylbenzene and solvent concentrations so that, in general, higher order clusters are not observed. Moreover, the ionization energy is determined to be just high enough to observe spectra but not cause extensive fragmentation into lower mass channels. All peaks in a given spectrum are found to have the same backing pressure dependence.

Ground-state potential energy profiles for the allylbenzenes are obtained by using Kao's molecular orbital-molecular mechanics MOMM-85 algorithm,^{14,15} a theoretical approach which has found to be applicable to aromatic molecules.^{14–16}

The resolution presently available to us (ca. 0.1 cm^{-1}) is not sufficient to determine the detailed geometries of allylbenzene clusters from rotational spectroscopy. Instead, potential energy Lennard-Jones (LJ) atom-atom (6–12–1) calculations¹⁷ are used in this endeavor. These calculations are similar to others used in the past and employ the same set of LJ potential parameters.^{18,19} The partial electronic charges centered on each atom of allylbenzene are listed in Table I and are obtained from ab initio STO-3G calculations.

For allylbenzene clustered to methane and ethane, the use of partial charges has no effect on the calculated cluster geometry

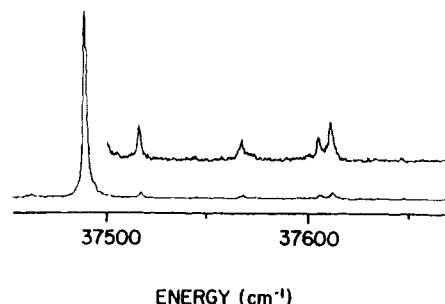


Figure 1. One-color TOFMS of the 0_0^0 region $S_1 \leftarrow S_0$ for jet-cooled allylbenzene. The single intense feature is assigned as the origin and occurs at $37\,492.6\text{ cm}^{-1}$. The weak features to higher energy of the origin are presumed to be due to torsional motion of the allyl group. The solitary origin demonstrates that only one molecular conformation exists as an energy minimum for this molecule.

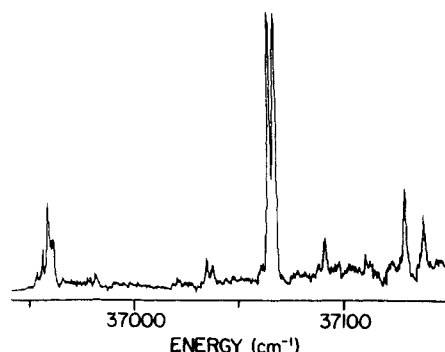


Figure 2. One-color TOFMS of the 0_0^0 of $S_1 \leftarrow S_0$ for jet-cooled 1-allyl-3-methylbenzene. The spectrum contains two origins at $37\,099.2$ and $37\,066.9\text{ cm}^{-1}$. The origins appear as doublets due to transitions between internal rotational states of the ring methyl group.

and only a small effect ($\sim 3\text{ cm}^{-1}$) on the calculated cluster binding energies. The partial charges are therefore omitted in these calculations.

Methane, ethane, water, and ammonia are typically mixed with the expansion gas at a concentration of 2% in 50–100 psig of helium.

Allylbenzene (1) and 1-allyl-2-methylbenzene (2) are purchased from Wiley Organics, Inc., and are used without further purification. The samples are all maintained at ca. 25°C during the experiment.

1-Allyl-3-methylbenzene (3).²⁰ A solution of 3-tolylmagnesium bromide, prepared from 3-bromotoluene (8.5 g, 49.7 mmol) and magnesium turnings (2.41 g, 99 mmol) in ether (20 mL), was added at room temperature to a mixture of allylisopropyl sulfide (4.0 g, 34.4 mmol) and $\text{NiCl}_2(\text{Ph}_2\text{PCH}_2\text{CH}_2\text{CH}_2\text{PPh}_2)^{16}$ (0.5 g, 0.92 mmol) in ether (80 mL). The reaction mixture was heated under reflux for 10 h, cooled, and quenched with 1 N hydrochloric acid. The organic phase was separated, filtered, dried (sodium sulfate), and concentrated at ca. 0°C (0.05 mmHg). The 1-allyl-3-methylbenzene (3) was then isolated by distillation to give 3.62 g (80%): bp $24\text{--}27^\circ\text{C}$ (0.05 mmHg); ^1H NMR (CDCl_3) δ 2.32 (s, 3 H), 3.34 (d, 2 H, $J = 6.7\text{ Hz}$), 5.03–5.11 (m, 2 H), 5.88–6.00 (m, 1 H), 6.97–7.20 (m, 5 H); ^{13}C NMR (CDCl_3) δ 21.36, 40.20, 115.63, 125.58, 126.78, 128.30, 129.34, 137.57, 137.95, 139.96.

III. Experimental Results

A. Allylbenzene and Allyltoluenes. The time-of-flight mass spectrum of the 0_0^0 band region for the $S_1 \leftarrow S_0$ transition of jet-cooled allylbenzene (1) is presented in Figure 1. The spectrum contains one origin, located at $37\,492.6\text{ cm}^{-1}$. This single origin indicates that only one energy minimum exists for the orientation

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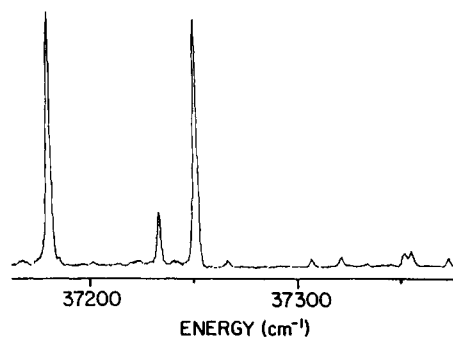


Figure 3. One-color TOFMS of the 0_0^0 region of $S_1 \leftarrow S_0$ for jet-cooled 1-allyl-2-methylbenzene. The spectrum contains two intense features at 37179.5 and 37250.8 cm^{-1} which are assigned as origins. The presence of two origins eliminates the conformation **5b** as the correct geometry of the energy minimum.

of the allyl group with respect to the ring in allylbenzene, as defined in **4a** and **4b**.

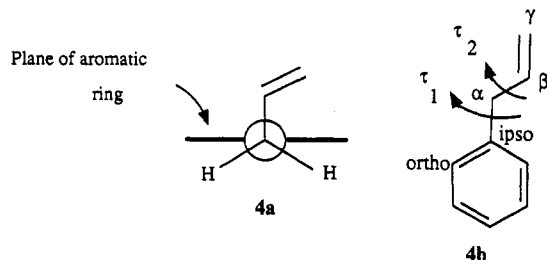


Figure 2 is the TOFMS of jet-cooled 1-allyl-3-methylbenzene (**3**). The spectrum exhibits what are assigned as two separate origins, at 36959.2 and 37066.9 cm^{-1} , belonging to different conformers. The origin at 36959.2 cm^{-1} appears weak because the laser output at this wavelength (LDS-698 doubled mixed with 1.064 μm) is quite low in intensity. As has been commonly observed for 1-alkyl-3-methylbenzenes,¹⁻⁴ the origins appear as doublets due to transitions between internal rotational states of the ring methyl group. This phenomenon is well-documented and understood¹⁻⁴ and will not be discussed here. Features to the low-energy side of the origin at 36959.2 cm^{-1} are possibly due to the torsional hot band of the allyl group. The TOFMS of jet-cooled 1-allyl-2-methylbenzene (**2**) is presented in Figure 3 and shows two intense features, at 37179.5 and 37250.8 cm^{-1} , which are also assigned as origins.

A portion of the steric energy function for allylbenzene (**1**) based on the MOMM^{14,15} algorithm is shown in Figure 4. MOMM calculations were also performed on 1-allyl-2-methylbenzene (**2**). In both cases, $\tau_1(\text{C}_{\text{ortho}}-\text{C}_{\text{ipso}}-\text{C}_{\alpha}-\text{C}_{\beta}) = \text{ca. } 90^\circ$; i.e., the allyl substituent is essentially orthogonal to the plane of the benzene ring (cf. **4**). This is consistent with the experimental and theoretical findings for τ_1 for other alkyl-substituted aromatics of partial structure ArCH_2R .^{1,3,4,15,22} The Newman projections for the conformational profile about $\tau_2(\text{C}_{\text{ipso}}-\text{C}_{\alpha}-\text{C}_{\beta}-\text{C}_{\gamma})$ represent the other important conformational variable for these compounds. The steric energy profile for rotation about τ_2 is shown in Figure 4. As can be seen, the vinyl/ $\text{C}_{\alpha}-\text{C}_{\text{ipso}}$ eclipsed **5a** and vinyl/ $\text{C}_{\alpha}-\text{H}_{\alpha}$ eclipsed **6a** (= **7a**) conformations are predicted to be the energy minima for allylbenzene. Because the energy difference between **5a** and **6a/7a** is small (<1 kcal/mol), certainly within the error range of the MOMM calculations, we cannot specify which of these is the global energy minimum. Much more refined calcu-

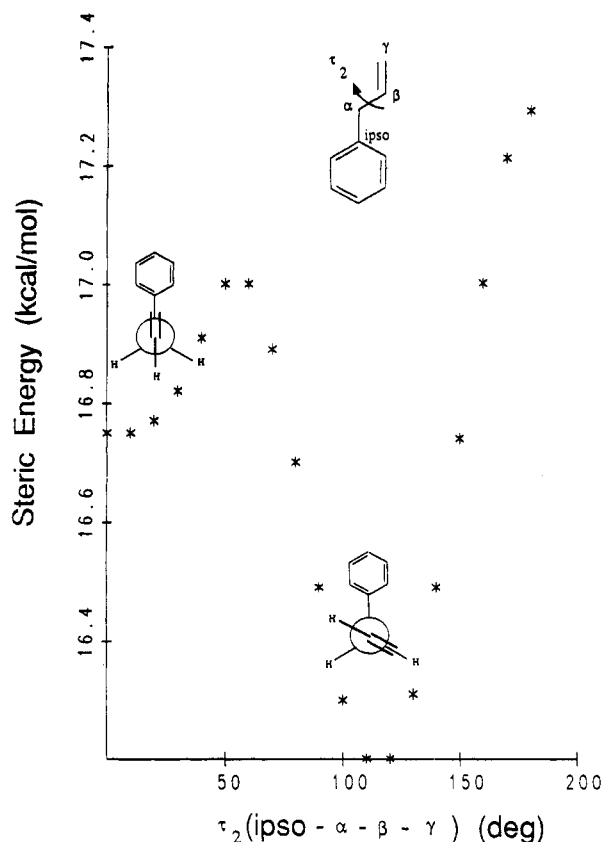


Figure 4. MOMM-derived steric energy profile for allylbenzene for rotation about τ_2 .

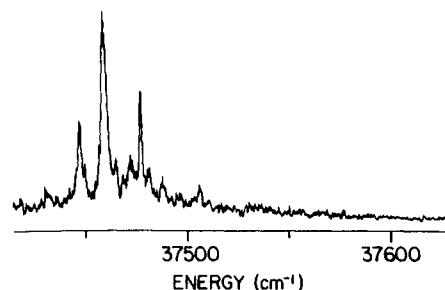


Figure 5. Two-color TOFMS of the 0_0^0 region of $S_1 \leftarrow S_0$ for jet-cooled allylbenzene(CH_4)₁. The three intense peaks occur at 45, 33, and 15 cm^{-1} to lower energy of the allylbenzene origin and are due to three different cluster configurations.

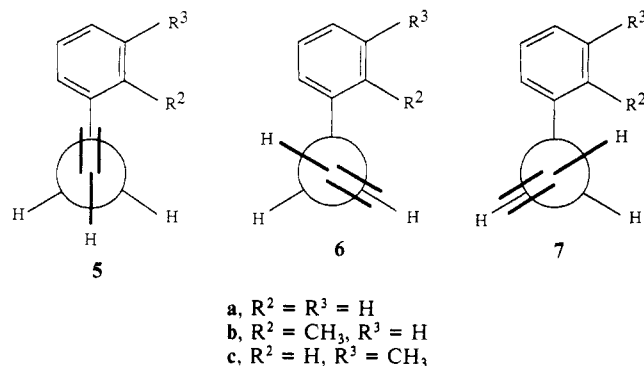
lations would be required before one could confidently predict which of **5-7** is the most stable conformation and what the energy difference between them is. For example, preliminary STO-3G calculations on the geometries of the MOMM-derived energy minima found for **1** (i.e., **5a** vs **6a**) led to a reversal of their potential energies (0.55 kcal/mol by MOMM, -2.40 kcal/mol by STO-3G). The important conclusion here is that the energy minimum is a vinyl/ $\text{C}_{\alpha}-\text{X}_{\alpha}$ eclipsed conformation, with X representing either the aromatic ring bond (as in **5**) or the α -hydrogen atom (as in **6** and **7**).²³

B. Allylbenzene/Methane. The TOFMS of allylbenzene clustered with one methane molecule ($\text{AB}(\text{CH}_4)_1$) is presented in Figure 5. Three relatively intense features occur at 37447.6, 37459.8, and 37477.9 cm^{-1} , red-shifted from the origin of allylbenzene by 45.0, 32.8, and 14.7 cm^{-1} . The first two shifts are similar to those observed for methane clustered to other substituted benzenes such as propylbenzene.¹³ For this latter case, shifts of -51 and -26 cm^{-1} are found for methane above and below the ring of the anti conformer.

In order to perform the usual LJ cluster potential energy geometry search calculations for the allylbenzene/solvent clusters, a geometry for the allylbenzene portion of the cluster must be

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(23) For allylbenzene, MNDO calculations reveal a minimum at $\tau_2 \approx 120^\circ$ and maxima at $\tau_2 \approx 0^\circ$ and 180° , while AM1 calculations reveal a global minimum at $\tau_2 \approx 140^\circ$ and a less stable minimum at $\tau_2 \approx 0^\circ$. MOMM, MNDO, and AM1 are reasonably consistent in that each predicts the energy minimum to be ca. $\tau_2 \approx 120^\circ$. We thank Professor Paul v. R. Schleyer and Dr. M. Bremer for providing the MNDO and AM1 results.



assumed. Conformer **6a** is chosen for the allylbenzene minimum-energy conformer: arguments in favor of this choice are presented in the Discussion section and are consistent with the aforementioned spectra. Potential energy calculations for $\text{AB}(\text{CH}_4)_1$ yield the five cluster geometries illustrated in Figure 6. Cluster binding energies are also presented in this figure. For only two of these geometries is the methane molecule coordinated directly to the aromatic π -system of the ring. These two structures are analogous to those observed for propylbenzene(CH_4)₁ and presumably are responsible for the 45-cm^{-1} (above the ring) and 32.8-cm^{-1} (below the ring) red-shifted features in Figure 5.

The remaining three structures in Figure 6 all involve methane coordination to the π -system of the allyl group. Such coordination should have a minimal effect on the energy of the $\pi^* \leftarrow \pi$ transition of the ring π -system, and therefore at least one of these three remaining cluster geometries must be responsible for the feature at $37\,477.9\text{ cm}^{-1}$ in Figure 5.

C. Allylbenzene/Ethane. The TOFMS of the allylbenzene-(C_2H_6)₁ van der Waals cluster 0_0^0 region is presented in Figure 7. The most intense feature of this spectrum occurs at $37\,489.8\text{ cm}^{-1}$ and is red-shifted from the allylbenzene origin by only 2.8 cm^{-1} . Some of the other features present in Figure 7 occur at $37\,418.8$, $37\,451.0$, $37\,499.1$, and $37\,512.4\text{ cm}^{-1}$, with corresponding shifts from the allylbenzene origin of -73.8 , -41.6 , 6.5 , and 19.8 cm^{-1} .

LJ potential energy calculations of allylbenzene(C_2H_6)₁ yield nine separate cluster geometries; these are depicted in Figure 8A,B. The first four of these are the familiar "perpendicular" and "parallel" configurations of the ethane molecule over the benzene ring and have been observed for ethane coordinated to benzene¹⁷ and propylbenzene.¹³ The perpendicular and parallel configurations of the benzene(C_2H_6)₁ cluster produce red shifts of the 0_0^0 transition of 57.2 and 50.8 cm^{-1} , respectively. Thus, these cluster geometries for allylbenzene(C_2H_6)₁ clusters are most likely responsible for the features at $37\,418.8$ and $37\,451.0\text{ cm}^{-1}$ (red shifts of 73.8 and 41.6 cm^{-1}) in Figure 7.

The most intense features of the spectrum in Figure 7 lie quite close to the allylbenzene origin. Such small red shifts are to be expected for clusters in which the aromatic π -system of the ring is not coordinated or solvated.¹³

The features at $37\,489.8$, $37\,499.1$, and $37\,512.4\text{ cm}^{-1}$ in Figure 7 are therefore most likely due to the coordination of the ethane molecule to the π -system of the allyl substituent.

D. Allylbenzene/Water. Figure 9 depicts the TOFMS of allylbenzene(H_2O)₁ in the region of the allylbenzene 0_0^0 transition. The first four intense features of the spectrum occur at $37\,523.5$, $37\,540.4$, $37\,577.7$, and $37\,582.9\text{ cm}^{-1}$, with corresponding blue shifts relative to the allylbenzene origin of 30.9 , 47.8 , 85.1 , and 90.3 cm^{-1} . LJ potential energy calculations reveal four separate allylbenzene(H_2O)₁ configurations, as shown in Figure 10. Two of these involve the coordination of the water molecule to the aromatic π -system above and below the ring. A cluster of similar geometry produces an 84.6-cm^{-1} blue shift of the 0_0^0 transition in benzene.¹⁸ The features in Figure 9 that are blue-shifted from the allylbenzene origin by 85.1 and 90.3 cm^{-1} are therefore most likely due to the coordination of the water molecule to the π -system of the ring. The features that are blue-shifted by 30.9 and 47.8 cm^{-1} are presumably due to (at least) coordination of the water

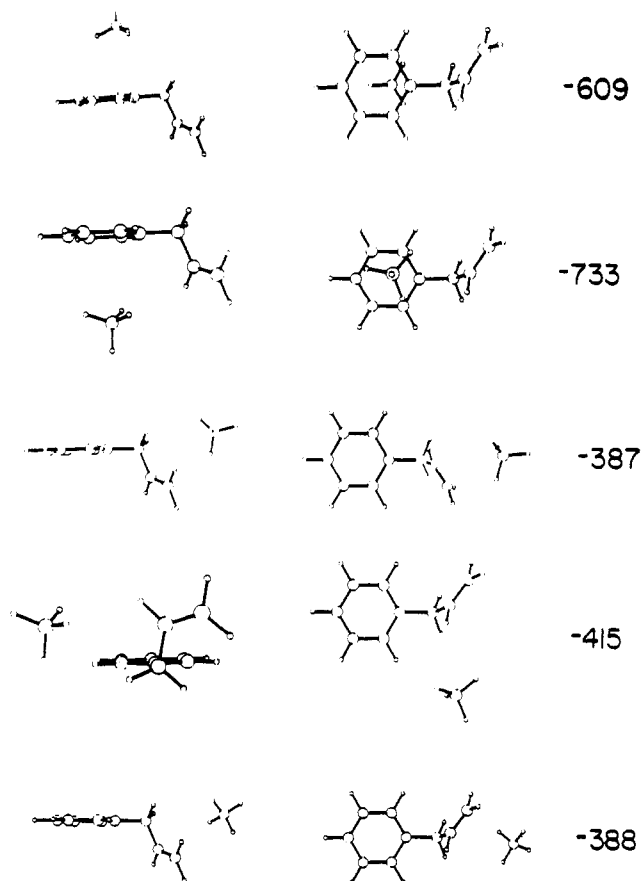


Figure 6. Minimum-energy cluster configurations and binding energies for allylbenzene(CH_4)₁ obtained from the Lennard-Jones potential energy calculation.

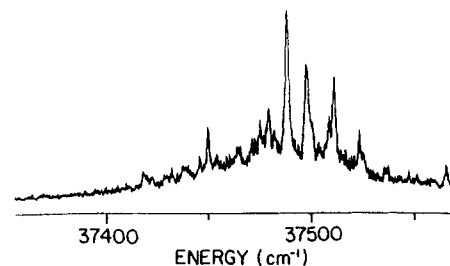


Figure 7. Two-color TOFMS of the 0_0^0 region of $S_1 \leftarrow S_0$ for jet-cooled allylbenzene(C_2H_6)₁. The intense features centered around $37\,500\text{ cm}^{-1}$ are within 20 cm^{-1} of the allylbenzene origin and are due to clustering of the ethane molecule on the allyl substituent.

molecule to the π -system of the allyl group.

E. Allylbenzene/Ammonia. The TOFMS of the 0_0^0 transition of allylbenzene(NH_3)₁ is presented in Figure 11. Intense features occur at $37\,490.6$, $37\,542.7$, and $37\,566.3\text{ cm}^{-1}$, shifted by -2.0 , $+50.1$, and $+73.7\text{ cm}^{-1}$, respectively, from the origin of allylbenzene. LJ potential energy calculations predict the existence of the four cluster configurations illustrated in Figure 12. As for water, two of these clusters involve coordination of the ammonia molecule to the π -system of the ring, while the other two involve ammonia coordination to the π -system of the allyl group. The TOFMS of ammonia coordinated to benzene is complex and difficult to interpret,¹⁸ but an assignment of these data has been presented.¹⁸ The red-most feature in the TOFMS is 100 cm^{-1} to lower energy of the benzene 0_0^0 transition. Other data for ammonia coordinated to alkyl-substituted benzenes are not presently available.

An ammonia molecule coordinated directly over the π -system of the aromatic ring of allylbenzene would unlikely produce only a 2-cm^{-1} red shift of the cluster 0_0^0 transition. Since solvation of or coordination to the aromatic ring π -system typically produces the largest cluster (red or blue) shifts, we assign the features in

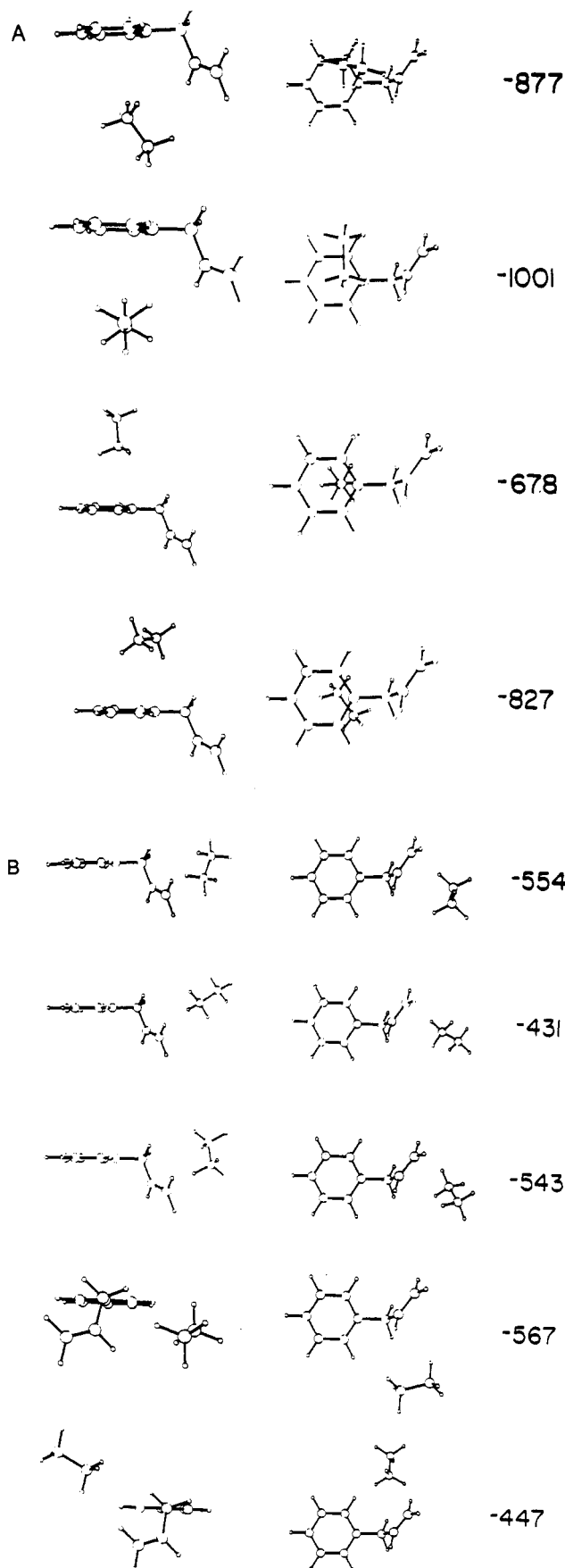


Figure 8. Minimum-energy configurations and binding energies for allylbenzene(C_2H_6)₁ obtained from LJ potential calculations: (A) complexation of ethane with aromatic π -system; (B) complexation of ethane with olefin π -system.

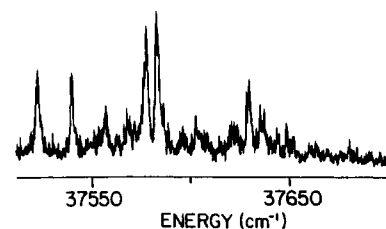


Figure 9. Two-color TOFMS of the 0_0^0 region of $S_1 \leftarrow S_0$ for jet-cooled allylbenzene(H_2O)₁. The spectrum contains four intense features at 37523.5, 37540.4, 37577.7, and 37582.9 cm^{-1} corresponding to four different cluster configurations.

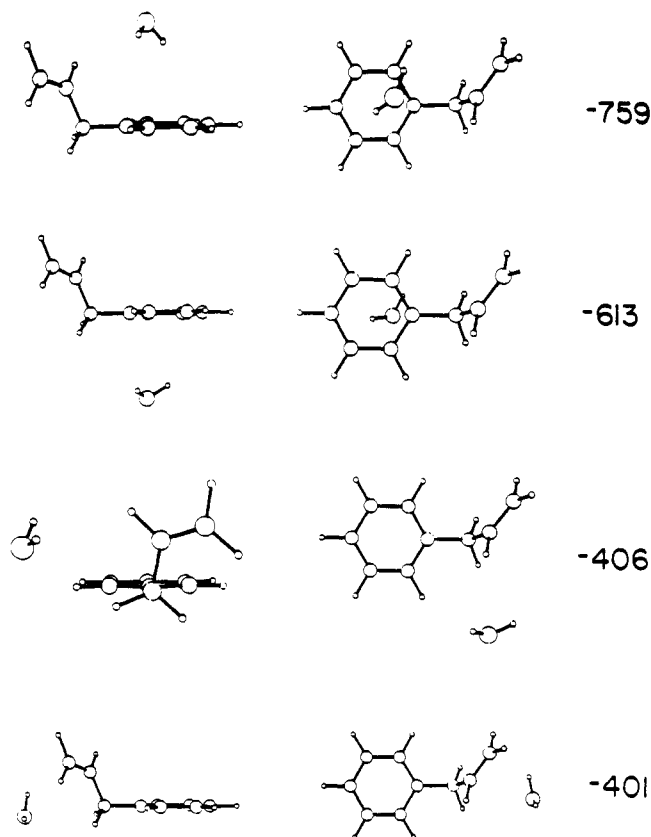


Figure 10. Minimum-energy configurations and binding energy for allylbenzene(H_2O)₁ obtained from LJ potential calculations.

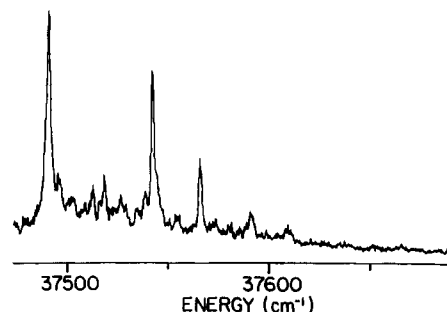


Figure 11. Two-color TOFMS of the 0_0^0 region of $S_1 \leftarrow S_0$ for jet-cooled allylbenzene(NH_3)₁. The intense features at 37490.6, 37542.7, and 37566.3 cm^{-1} are due to different cluster configurations.

Figure 11 that are blue-shifted 50.1 and 73.7 cm^{-1} from the allylbenzene origin to transitions belonging to clusters in which the ammonia is positioned directly over the ring. The 2.0- cm^{-1} red-shifted feature is most likely due to a cluster in which the ammonia molecule is directly coordinated to the allyl substituent.

IV. Discussion

A. Allylbenzene Conformation. In previous studies, we have demonstrated that laser jet spectroscopy can be employed to

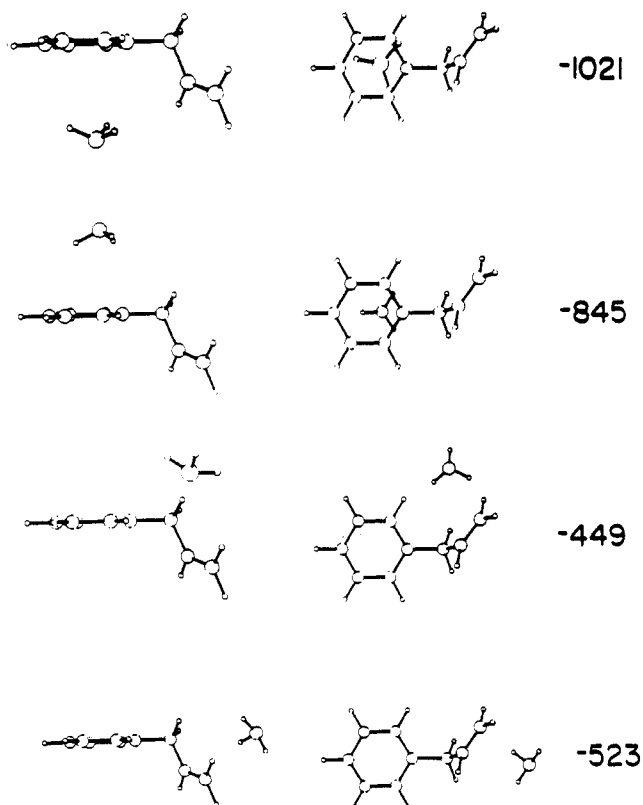


Figure 12. Minimum-energy configurations and binding energies for allylbenzene(NH_3)₁, obtained from LJ potential calculations.

observe stable conformational isomers, even if the energy barriers for conformational interconversion are very low.¹⁻⁷ In each spectrum, the origin transition is associated with a specific stable ground-state conformation; conversely, each stable conformation corresponding to a potential energy minimum generates, at least in principle, its own spectroscopic 0_0^0 transition. Hence, by examining the spectra of specifically substituted allylbenzenes, one can in principle "count" the number of stable ground-state conformations and thereby establish their molecular geometries.¹⁻⁷ For allylbenzenes, this may lead to a distinction between **5** and **6/7** or the possible presence of both in the jet.

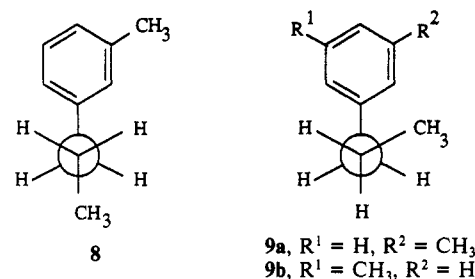
As shown in Figure 4, a variety of stable conformations can be proposed for **1-3**; however, only conformations for which the allyl substituent is essentially perpendicular to the plane of the benzene ring are considered in this discussion, since MOMM calculations indicate $\tau_1 \sim 90^\circ$. Moreover, such orientations are found experimentally and theoretically to be the energy minima for all other aryl-primary alkyl ($\text{Ar}-\text{CH}_2-\text{R}$) compounds (e.g., ethyl, propyl, isobutyl, neopentyl, etc.).^{1,3,4,15,22} The MOMM results point to **5** and **6/7** as stable ground-state conformations.

Since only a single origin transition is observed for **1**, either **5a** or **6a** ($=7a$) but not both conformations obtains for allylbenzene; analogously only **5b** or the "mixture" of [**6b** and **7b**] obtains for **2**. To distinguish between these possibilities, we have utilized these asymmetrically substituted allylbenzenes following the strategy employed previously by us to uncover the minimum-energy conformations of alkyl- and methoxy-substituted benzenes.¹⁻⁷

Consider 1-allyl-2-methylbenzene (**2**): the TOFMS of this compound would contain only one origin transition if conformation **5b** were the energy minimum, while conformations **6b** and **7b** would yield two distinct origins. Since the actual TOFMS of 1-allyl-2-methylbenzene, presented in Figure 3, contains two origins, at 37 179.5 and 37 250.8 cm^{-1} , conformation **5a** is ruled out. Thus, conformations **6b** and **7b** are assigned as the stable conformations of **2**.

Similar logic obtains for 1-allyl-3-methylbenzene (**3**). As shown in Figure 2 and discussed above, two origin transitions are observed and assigned as **6c** and **7c**. Although we have made assignments

linking specific conformations with individual transitions for other systems, as in the case of the anti **8** and two gauche **9a** and **9b** conformations observed for propylbenzene,³ we cannot at this time assign the individual transitions observed for **2** and **3** to specific conformations **6** or **7**.



B. Allylbenzene Clusters. The π -system of the double bond in allylbenzene can and does compete effectively with the π -system of the aromatic ring to coordinate incoming solvent molecules. Coordination with this olefinic π -system results in stable clusters with various solvent molecules. In addition, the geometries of clusters in which the solvent molecule is coordinated to the ring are influenced by the double bond of the allyl group, which tends to pull the solvent molecule to the allyl side of the ring. Thus, the early (and perhaps later) stages of nucleation and solvation of olefin-substituted benzene derivatives may well differ substantially from those of alkane-substituted benzene derivatives.

Allylbenzene/water and allylbenzene/ammonia clusters for which the solvent is coordinated to the aromatic ring apparently generate blue-shifted 0_0^0 transitions with respect to the allylbenzene isolated molecule. This excited-state reduced binding energy is probably related in the fact that these solvent molecules contain lone pairs of electrons which can destabilize the π^* -state of the ring relative to the ground state. Very similar behavior is found and characterized for other aromatic systems.^{12,13,17-19}

Finally, the fact that the coordination of solvent molecules to the allyl substituent generally has only minor effects on the energy of the ring $\pi^* \leftarrow \pi$ transition indicates that the two π -electronic systems are indeed reasonably isolated from each other.

V. Conclusions

We have observed spectra of the isolated allylbenzenes **1-3** and allylbenzene itself solvated by various small molecules (CH_4 , C_2H_6 , NH_3 , H_2O). Based on both spectroscopic and theoretical results, the ground-state energy minimum geometry of isolated allylbenzene is determined to be **6a** ($=7a$). For **2**, conformations **6b** and **7b** are found to be the ground-state energy minima. Similarly, for **3**, conformations **6c** and **7c** are the ground-state energy minima. Allylbenzene clusters appear to have two very distinct types of spectra: those well shifted (red or blue) from the comparable allylbenzene feature and those relatively near the comparable allylbenzene feature. The former spectra we have associated with clusters in which the solvent is directly coordinated to the aromatic ring, and the latter spectra we have associated with clusters in which the solvent is coordinated to the allyl group π -system, well removed from the ring and the $\pi^* \leftarrow \pi$ transition. Solvation does not appear to disrupt in any way the conformation of the isolated allylbenzene molecule, as the spectral shifts characterized for the clusters are all relatively small and well within the range found for other simple aromatic systems. And finally, since much of the cluster spectroscopic intensity seems to be found in features associated with allyl group direct solvation (origin features with small cluster shifts), we suggest that the allyl π -system has a significant influence upon how allylbenzene interacts with and is solvated by small solvent molecules.

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