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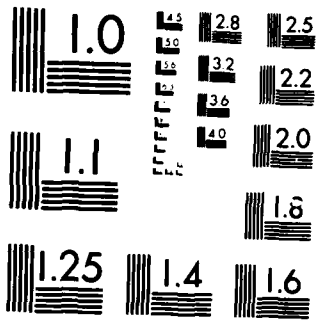
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MOLECULAR JET STUDY OF VAN DER WAALS COMPLEXES OF FLEXIBLE MOLECULES:

n-PROPYL BENZENE SOLVATED BY SMALL ALKANES

by

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in the
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A combination of atom-atom potential calculations and experimental molecular jet spectroscopic studies is used to elucidate the geometry and binding energy of n-propyl benzene/methane, ethane, and propane clusters. Two color time-of-flight mass spectroscopy data and calculations are presented for both trans and gauche configurations of n-propyl benzene with up to three hydrocarbon molecules of solvation. Cluster shifts and geometry are treated in detail for the observed and calculated systems. Solvation, as observed in the clusters, see 15 to have little effect on the geometry of the solute in this instance.		

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20. Alkyl chain motion is also discussed for the n-propyl benzene isolated molecule.

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Van der Waals Clusters

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I. INTRODUCTION

Supersonic molecular jet spectroscopy of van der Waals (vdW) clusters is capable of generating information which can lead to a fundamental understanding of intermolecular interactions. The vdW cluster shift, binding energy, and energy dissipation dynamics are experimental observations essential for the characterization of the solvation state and processes.¹ The cluster shift has become of particular interest: besides being dependent on the polarizability of the solvent and solute molecules, the cluster shift is a sensitive function of the cluster geometry^{1a,2} and thereby the local site details of the intermolecular potential.

In addition, the study of vdW complexes consisting of a flexible solute molecule solvated by small hydrocarbons is of interest for at least two reasons. First, information is obtained on the effect of solvation on solute geometry. Second, if the solute molecule assumes a few special geometries, the effect of these different geometries on the solvation processes themselves can be measured. The present study of n-propyl benzene (npb) sheds light mainly on this latter issue.

Solvation studies of npb should provide a unique opportunity to pursue the above relationships further as npb exhibits two distinct conformations in a supersonic expansion - trans and gauche.³ [We adopt the nomenclature of reference 3 for convenience and to avoid confusion; however, we feel trans and cis are probably more appropriate and consistent terms for npb.] In the trans



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conformation (ntpb), the propyl chain extends away from the aromatic ring, whereas in the gauche conformation (ngpb), the propyl chain folds back over the ring and partially covers one side of it (see fig 1). Thus, both the top and bottom of the ring are exposed in ntpb and are expected to provide lowest energy binding sites for solvent molecules.² Only one side of the ring ("the bottom") is completely exposed for binding solvent in the gauche conformation. Solvation of ntpb and ngpb by small hydrocarbons should yield different cluster shifts as the cluster geometries are expected to be modified by the two different conformations of the propyl chain.

Some preliminary information on the solvation of npb by helium is already available.^{3a} Two features, assigned to $\text{ntpb}(\text{He})_{1,2}$, are reported on the high energy side of the ntpb first singlet 0_0^0 transition: the features are identified as belonging to the ntpb ring centered He complexes. Under the same experimental conditions only one blue shifted feature is formed for the 0_0^0 transition of ngpb. This latter observation is attributed to the partial blocking of a potential ring binding site by the propyl side chain and thus only one He-ngpb complex is readily formed.

The present work examines the solvation of npb by methane, ethane, and propane molecules. We report on three specific investigations in the paper: 1) 0_0^0 absorption spectra observed through 2-color photoionization time of flight mass spectroscopy (2-color MS); 2) 2-color MS studies of higher vibrational levels of the excited state to determine binding energies; and 3) atom-atom potential calculations (exp-6) to predict the minimum energy configurations of different clusters.

Through these studies it is found that the binding energies of npb-alkane clusters are similar to those of the comparable toluene-alkane clusters.^{2a} The presence of the propyl chain, however, in npb generates additional interactions which significantly modify the overall cluster geometry. The binding sites for an alkane solvent molecule above (A, on the same side as the propyl chain) or below (B, on the side opposite from the propyl chain) the aromatic ring are not equivalent. The data obtained in these studies suggest that rotation of the propyl chain does not occur about the phenyl-alkyl bond (C₁-C₇) or the C₇-C₈ bond.

II. EXPERIMENTAL PROCEDURES

The procedures for obtaining 2-color MS absorption spectra and the apparatus employed for this study have been described in detail previously.^{1a} Commercial grade npb is used in this work without purification. Two Quanta Ray Nd:YAG lasers are used to pump two dye laser-doubling systems which provide the pump and ionization beams. The excitation to S₁ of npb is accomplished with doubled Coumarin 500 dye output. S₁ to npb⁺ ionization is affected by doubled R640 output (I.P.=8.72ev).⁴ The expensive, short lived Coumarin 500 dye is recovered by recrystallization techniques.⁵

Calibration of the absorption spectra is provided by the optogalvanic effect for a Fe:Ne hollow cathode lamp. The absolute positions of spectral features are accurate to $\pm 1.0\text{cm}^{-1}$.

Atom-atom potential calculations employ the simple exponential-6 form,

$$E_{ij} = - \frac{A_{ij}}{R_{ij}^6} + B_{ij} \exp [-C_{ij} R_{ij}].$$

The aromatic coefficients A, B, and C of benzene are used for npb.⁶ The aliphatic coefficients of ethane and propane are assumed to be the same as those of methane.⁷ The aliphatic-aromatic (al-ar) coefficients are derived as follows:

$$A_{al-ar} = (A_{al-al} A_{ar-ar})^{1/2}$$

$$B_{al-ar} = (B_{al-al} B_{ar-ar})^{1/2}$$

$$C_{al-ar} = \frac{1}{2}(C_{al-al} + C_{ar-ar})$$

The complete set of coefficients employed in this study is given in Table I.

The calculation is carried out with an HP 9845 S computer. The aromatic ring of the npb solute molecule is held fixed in the XY plane with the coordinate system origin at the ring center. The propyl chain is assumed to be fixed (see fig 1) and in the +Z direction above (A) the plane of the ring in either the g or t configuration. The carbon atoms of the propyl chain are in the molecular symmetry plane perpendicular to the plane of the ring.

The alkane solvent molecule is introduced systematically in a random orientation relative to npb and the sum of the nonbonded atom pair energies is minimized with respect to the six degrees of rotational and translational freedom of the solvent molecule. The total energy of the cluster is minimized with an increment or decrement of 0.01 \AA^0 for translational and 1° for

rotational motion until a local energy minimum is found. This general process is then repeated by introducing the alkane solvent molecule in another orientation relative to npb until all reasonable local minima are located. For clusters involving two alkane solvent molecules, only one solvent molecule is allowed to move at a time: many interactions are required to achieve a local energy minimum in this instance. In general, two or three local minima are found for a specific npb-alkane cluster. Only the minimum energy configuration, or configurations nearly isoenergetic with it, are chosen as optimum cluster conformations.

III. RESULTS

Detailed 2-color MS study of npb-(C_yH_{2y+2})_x (y<3, x<3) clusters is limited to the 0₀⁰ transitions as this region is relatively free of spectral congestion. Higher vibronic transitions are probed only to bracket the cluster binding energies. Fluorescence excitation and dispersed emission studies are omitted from this report because: a) the fluorescence excitation experiment is not mass selective and it thus produces only redundant information; b) preliminary 2-color MS studies indicate (npb)₂ has a strong absorption in the spectral region of interest;⁸ and c) dispersed emission studies of the toluene-alkane systems show extensive intramolecular vibrational redistribution⁹ and npb-alkane clusters are expected to behave similarly.

In this section we present experimental and calculational data on the cluster 0₀⁰ spectra and binding energies. We begin, however, with a short description of the npb spectra.

A. npb Spectra.

In order to understand the 2-color MS spectra of npb-alkane clusters, a description of the absorption spectrum of the npb molecule itself is necessary. A portion of the npb 2-color MS spectrum near the electronic origin is presented in figure 1. The two nearly equal intensity bands at 37,533.9 and 37,583.1 cm^{-1} correspond to the electronic origins of ngpb and ntpb, respectively. The 0_0^0 of ngpb is red shifted 49.2 cm^{-1} relative to the 0_0^0 of ntpb due to a "self-solvation" of the aromatic ring by the propyl group.^{3a} The two weak features at 37,572.9 and 37,613.9 cm^{-1} are probably related to the hindered rotations of parts of the propyl chain (in particular, the terminal methyl group).

B. Origin Cluster Spectra.

The assignment of the cluster spectra largely relies on the potential calculations and the experience obtained from toluene-alkane and benzene-alkane systems reported previously from our laboratory.² The present calculations suggest that the preferred binding sites in npb are above (A,+Z) and below (B,-Z) the aromatic ring. [Recall that the t or g propyl chain is assumed to be above the ring.] A general consistent picture emerges through consideration of the observed 2-color MS spectra and the calculated minimum energy cluster configuration. The cluster red shift appears to be strongly dependent on the effective interaction ("distance") between the solvent molecule and the π -cloud of the aromatic ring of npb: the larger interaction is associated with the larger cluster red shift. Similar results are reported for toluene-alkane and benzene-alkane systems.

For a ring centered toluene-or benzene-alkane cluster, the cluster red shift of the $S_1^+ S_0$ transition is $\sim 55 \pm 15 \text{ cm}^{-1}$; the exact number depends upon the solvent molecule involved. The npb cluster shifts are expected to be somewhat larger than this because npb probably has a larger polarizability than toluene or benzene.

In the following assignment and analysis of the spectra of the various npb-solvent clusters, the transitions for each cluster are typically presented in order of increasing energy. We have done this to allow the reader to follow the logic of the assignments free from the prejudice of an overriding theme. The general trends and systematics of the results will be outlined in the Discussion Section.

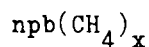


Figure 2 (bottom trace) depicts the 2-color MS spectrum of the $\text{npb}(\text{CH}_4)_1$ origin. The band at -93.4 cm^{-1} relative to the $\text{ntpb } 0_0^0$ (-44.2 cm^{-1} relative to the 0_0^0 of ngpb) is assigned as the 0_0^0 of the B configuration of $\text{ngpb}(\text{CH}_4)_1$ (see fig 3). Potential calculations indicate both the A (above the ring, with the chain) and B (below the ring, away from the chain) configurations of $\text{ngpb}(\text{CH}_4)_1$ are possible with similar binding energies. However, in the A configuration the methane molecule has a considerable displacement from the ring center and a concomitant large interaction with the terminal methyl group of the propyl chain of ngpb . The A configuration of ngpb is therefore not likely to have a cluster shift as large as -40 cm^{-1} : we have, in fact, been unable to identify the A $\text{ngpb}(\text{CH}_4)_1$ configuration in the $\text{npb}(\text{CH}_4)_1$ spectra.

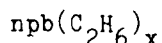
The intense peak at -51 cm^{-1} relative to the ntpb 0_0^0 can be assigned as the 0_0^0 of the A configuration of ntpb(CH₄)₁. This feature is followed by progressions in vdW stretching and bending modes: tentative assignments are tabulated in Table II. In the ntpb A configuration the methane molecule centers above the aromatic ring as shown in figure 3 and thus generates a considerable cluster spectral shift. Repeated measurements of the doublet structure at -26 cm^{-1} indicate that this doublet structure is not an experimental artifact. One of these components is reasonably assigned as a stretch built on the A ntpb(CH₄)₁ origin; the other feature, however, must derive from another configuration of ntpb(CH₄)₁. Potential calculations suggest that the only other configuration of ntpb(CH₄)₁ which has a significant binding energy is the B configuration (see fig 3).

The calculations indicate that the CH₄ molecule in the B configuration is shifted towards the propyl chain and away from the ring center. Based on these assignments, the propyl chain has a significant influence on the overall cluster geometry and spectral shifts.

The tentative assignments of the 2-color MS spectrum of npb(CH₄)₂ (see fig 2, middle trace) are given in Table II. The assignments are made with the support of the potential calculations and in conjunction with the above observations. Coordination of a CH₄ solvent molecule above the aromatic ring (at the A site) of the B configuration of npb(CH₄)₁ would probably have only a small effect on the B npb(CH₄)₁ cluster shift because, as can be seen in figure 3, this second "A methane" has a relatively small

direct interaction with the aromatic ring. Thus the band at -96.4 cm^{-1} (-47.2 cm^{-1} relative to the 0_0^0 of ngpb) may well be the AB configuration of $\text{ngpb}(\text{CH}_4)_2$, as the BB configuration would have an increased shift (see $\text{ngpb}(\text{C}_2\text{H}_6)_1$ assignment below). The intense feature at -70 cm^{-1} can be reasonably be assigned as the 0_0^0 of the AB configuration of $\text{ntpb}(\text{CH}_4)_2$ based on the nearly additive ($51 + 26 \text{ cm}^{-1}$) spectral shifts for this peak. Potential calculations also identify both the AA and BB $\text{ntpb}(\text{CH}_4)_2$ configurations as stable with good binding energies; the AA configuration should have the larger of the two spectral shifts (see fig 3). The bands at -58.6 and -36.2 cm^{-1} are thereby assigned as the 0_0^0 transitions of the AA and BB configurations of $\text{ntpb}(\text{CH}_4)_2$, respectively.

Figure 2 (top trace) presents the 2-color MS spectrum of $\text{npb}(\text{CH}_4)_3$. Two main features are apparent above a broad background. The bands at -103.2 cm^{-1} (-54 cm^{-1} relative to the 0_0^0 of ngpb) and -77.6 cm^{-1} appear to correspond to the 0_0^0 transitions of the ABB configurations of $\text{ngpb}(\text{CH}_4)_3$ and $\text{ntpb}(\text{CH}_4)_3$, respectively. Again, additivity of cluster spectral shift is the main factor in the assignment. The weak feature at -139.7 cm^{-1} remains at present unassigned.



The 2-color MS detected spectrum of $\text{npb}(\text{C}_2\text{H}_6)_1$ evidences a rich array of spectral features (see fig 4, bottom trace). Calculations indicate that the ethane atomic coordinates of the B configurations of $\text{ngpb}(\text{C}_2\text{H}_6)_1$ and $\text{ntpb}(\text{C}_2\text{H}_6)_1$ are quite similar; a detailed examination of the coordinates, however, reveals that the π -cloud solvent interaction is a little stronger for the $\text{ngpb}(\text{C}_2\text{H}_6)_1$ B configuration. Hence, we assign the bands

at -80.6 cm^{-1} (-31.4 cm^{-1} relative to the 0_0^0 band of ngpb) and -26.3 cm^{-1} as the 0_0^0 transitions of the B configurations of $\text{ngpb}(\text{C}_2\text{H}_6)_1$ and $\text{ntpb}(\text{C}_2\text{H}_6)_1$, respectively. The intense peak at -62.8 cm^{-1} probably corresponds to the 0_0^0 of the A configuration of $\text{ntpb}(\text{C}_2\text{H}_6)_1$ since the ethane solvent apparently has the largest effective interaction with the aromatic ring in this geometry (see fig. 5). The remaining features in the spectrum can be assigned as vdW vibrations of the $\text{npb}(\text{C}_2\text{H}_6)_1$ clusters built on these three origins (ntpb A, ntpb B and ngpb B). Detailed but tentative assignments of these spectra are presented in Table III. We are unable to identify an A $\text{ngpb}(\text{C}_2\text{H}_6)_1$ species in the observed spectrum of $\text{npb}(\text{C}_2\text{H}_6)_1$.

The 2-color MS spectrum of $\text{npb}(\text{C}_2\text{H}_6)_2$ is quite complicated (fig 4, middle trace): suggested assignments are presented in Table III. The assignments are made in accordance with the observed data for $\text{npb}(\text{C}_2\text{H}_6)_1$ and the potential calculations for $\text{npb}(\text{C}_2\text{H}_6)_2$. The -85.2 cm^{-1} feature is assigned as the 0_0^0 of the AB configuration of $\text{ntpb}(\text{C}_2\text{H}_6)_2$ based on the additive ($26.3 + 62.8 \text{ cm}^{-1}$) spectral shift. The -96.8 cm^{-1} (-47.6 cm^{-1} relative to the 0_0^0 of ngpb) and -48.7 cm^{-1} bands are most probably the 0_0^0 transitions of the BB configurations of the $\text{ngpb}(\text{C}_2\text{H}_6)_2$ and $\text{ntpb}(\text{C}_2\text{H}_6)_2$ clusters. The latter identifications derive from the calculations and $\text{npb}(\text{C}_2\text{H}_6)_1$ data. The most intense band at -58.4 cm^{-1} is assigned as the 0_0^0 of the AA $\text{ntpb}(\text{C}_2\text{H}_6)_2$ configuration. In this configuration the interaction between the solvent and the aromatic ring of ntpb derives essentially from only one of the ethane molecules (see fig 5).

The major features in the 2-color MS spectrum of $\text{npb}(\text{C}_2\text{H}_6)_3$ (fig 4 top trace) appear in the proximity of the 0_0^0 of ntp (-35 to $+2 \text{ cm}^{-1}$). Such features provide evidence for heterogeneous nucleation² as the dominant solvation process under the present beam conditions. In this process, the solvent molecules form a cluster before interacting with the solute species. Solvent-solvent interactions in the final solute-solvent cluster tend to reduce the number and strength of the solvent-solute interactions, eventually leading to smaller cluster red shifts. The relative positions of the major features in this spectrum are presented in Table III.

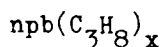


Figure 6 (bottom trace) presents the 2-color MS spectrum of $\text{npb}(\text{C}_3\text{H}_8)_1$. The intense band at -52.2 cm^{-1} is assigned as the A configuration of $\text{ntp}(\text{C}_3\text{H}_8)_1$. Note that this spectral shift is nearly identical to that observed for the A configuration of $\text{ntp}(\text{CH}_4)_1$. Calculations suggest that the effective interaction between the propane solvent molecule and the aromatic ring derives mainly from the interaction of the propane terminal methyl group and the ring (see fig 7). The atomic coordinates of the B configuration of $\text{ngpb}(\text{C}_3\text{H}_8)_1$ and $\text{ntp}(\text{C}_3\text{H}_8)_1$ are quite similar; however, the B $\text{ngpb}(\text{C}_3\text{H}_8)_1$ configuration evidences a somewhat larger interaction between the propane molecule and the aromatic ring. Hence, we assign the bands at -74.1 cm^{-1} (-24.9 cm^{-1} relative to the 0_0^0 of ngpb) and -16.9 cm^{-1} as the 0_0^0 transitions of the B configurations of $\text{ngpb}(\text{C}_3\text{H}_8)_1$ and $\text{ntp}(\text{C}_3\text{H}_8)_1$, respectively. The tentative assignments of most of the observed $\text{npb}(\text{C}_3\text{H}_8)_1$ spectral features can be found in Table IV.

The most intense feature in the 2-color MS spectrum of $\text{npb}(\text{C}_3\text{H}_8)_2$ appears at -68.5 cm^{-1} relative to the ntpb origin (fig 6, middle trace); this transition can be assigned as the 0_0^0 of the AB configuration of $\text{ntpb}(\text{C}_3\text{H}_8)_2$ based on its additive ($16.9 + 52.2 \text{ cm}^{-1}$) spectral red shift. The next most intense peak (at -75.8 cm^{-1} and -26.6 cm^{-1} relative to the 0_0^0 of ngpb) probably corresponds to the AB configuration of $\text{ngpb}(\text{C}_3\text{H}_8)_2$ since the binding of the propane molecule above (A position) the ring has little contribution to the overall cluster shift. The BB configuration of $\text{ngpb}(\text{C}_3\text{H}_8)_2$ should have a somewhat larger cluster shift than that found for $\text{ntpb}(\text{C}_3\text{H}_8)_2$ as suggested by the calculations. We therefore assign the bands at -81 cm^{-1} (-32 cm^{-1} relative to the $\text{ngpb } 0_0^0$) and -28.8 cm^{-1} as the 0_0^0 transitions of the BB configuration of $\text{ngpb}(\text{C}_3\text{H}_8)_2$ and $\text{ntpb}(\text{C}_3\text{H}_8)_2$, respectively. Tentative vibronic assignments are found in Table IV.

Figure 6 (top trace) shows the $\text{npb}(\text{C}_3\text{H}_8)_3$ 2-color MS spectrum. No attempt is made to assign these data at this time. The relative positions of the major features are given in Table IV.

C. Cluster Binding Energies.

The binding energies of npb -alkane clusters are found through two experiments: 2-color MS from high vibronic levels and potential calculations. The binding energies obtained by these two methods are consistent with one another and are similar to those of the comparable toluene-alkane clusters.² 2-color MS ion signals are observed for all npb -alkane clusters at the $6b^1$ level ($0^0 + 530 \text{ cm}^{-1}$). Due to the weak intensity of the 1_0^1 transition (10% of the 0_0^0 intensity), no conclusive determination of the ion signal can

be made. At 12^1 ($0^0 + 932 \text{ cm}^{-1}$) and 18_a^1 ($0^0 + 966 \text{ cm}^{-1}$) no ion signals for $\text{npb}(\text{CH}_4)_x$ can be observed. On the other hand, at $18a^1$ a weak, broad signal is found for $\text{npb}(\text{C}_2\text{H}_6)_1$ and a relatively sharp series of features is found for $\text{npb}(\text{C}_3\text{H}_8)_1$. We therefore conclude that the binding energies (D_0) for $\text{npb}(\text{CH}_4)_1$, $\text{npb}(\text{C}_2\text{H}_6)_1$, and $\text{npb}(\text{C}_3\text{H}_8)_1$ are $530 < D_0 < 933 \text{ cm}^{-1}$, $D_0 \sim 930 \text{ cm}^{-1}$, and $D_0 > 966 \text{ cm}^{-1}$, respectively, in the first excited singlet state.

The calculated binding energies for the observed clusters are found to fall within the limits of the experimental binding energies cited above. In general, different geometries of the same cluster have very similar binding energies. For example, all $\text{npb}(\text{CH}_4)_1$ clusters have a calculated binding energy of $700 \pm 10\% \text{ cm}^{-1}$, all $\text{npb}(\text{C}_2\text{H}_6)_1$ clusters have a binding energy of $900 \text{ cm}^{-1} \pm 5\%$, and all $\text{npb}(\text{C}_3\text{H}_8)_1$ clusters have a binding energy of $1125 \text{ cm}^{-1} \pm 5\%$. The $\text{npb}(\text{solvent})_2$ clusters vary in a similar manner with binding energies roughly twice those of the respective mono solvated npb. Energy spreads of roughly 10-15% within a given species are found for the $\text{npb}(\text{solvent})_2$ clusters. Given the calculational uncertainties for a particular set of potential parameters and a particular potential form ($\exp(-6)$), we consider the binding energy differences for a given cluster series (i.e., $\text{ntp}(\text{CH}_4)_2$, $\text{ngpb}(\text{CH}_4)_2$, AB, AA, BB) to be of no fundamental significance.

IV DISCUSSION

Both calculations and experiments find that more than one nearly isoenergetic conformer exist for many of the clusters. Analysis of the spectra would have been extremely difficult and much less informative without

the aid of the calculations. Potential calculations offer a viable alternative to high resolution rotational spectroscopy of clusters (presently under way in our laboratory, nonetheless). The admittedly crude exp-6 potential model employed in these calculations faithfully predicts the binding energies of toluene-alkane,^{2a} benzene-alkane,^{2b} and npb-alkane clusters. Replacing the composite atom-atom potential parameters with ab initio calculations of the intermolecular interactions between the alkane and npb molecules would be an improvement, however. Addition of charge terms and/or multipole molecular moments would also probably make cluster geometries more accurate and reliable.

In the discussion below a more in depth treatment of cluster geometry, cluster shift and the possible relative motions of the propyl chain in the npb molecule will be presented.

A. Cluster Geometry

Cluster geometries are mainly derived from potential calculations and expectations based on experience with benzene and toluene systems.² In general two configurations, above (A) and below (B) the plane of the aromatic ring as defined by the propyl chain (A), with roughly equal binding energies, are predicted for $\text{ngpb}(\text{C}_y\text{H}_{2y+2})_1$ and $\text{ntpb}(\text{C}_y\text{H}_{2y+2})_1$ ($y \leq 3$). These geometries are depicted in figures 3,5, and 7. In the A configurations of $\text{ntpb}(\text{C}_y\text{H}_{2y+2})_1$ the alkane molecules are nearly centered above the aromatic ring and apparently interact significantly with the π -system of the ring. The alkane molecules in the $\text{ngpb}(\text{C}_y\text{H}_{2y+2})_1$ clusters are, however, displaced 1.25Å along the X-axis (C_1 - C_7) away from the ring center and considerable interaction is found between the terminal methyl group of the propyl chain and the alkane

molecule in this configuration (see fig 3,5,7). Thus the geometry in such complexes leads to an apparently small effective interaction between the solvent molecules and the π -cloud of the aromatic ring. Both the two B configurations of $\text{npb}(\text{C}_y\text{H}_{2y+2})_1$ are quite similar in terms of coordinates, with the alkane solvent molecules displaced along the +X direction toward the propyl chain: the +X direction displacement of the solvent is about 10% greater for $\text{ntpb}(\text{CH}_4)_1$ than for $\text{ngpb}(\text{CH}_4)_1$. Three general configurations of substantial binding energy are calculated for $\text{npb}(\text{C}_y\text{H}_{2y+2})_2$ clusters: AB, AA, and BB. The AB configuration geometry is essentially the composite geometry of the configuration A and B of $\text{npb}(\text{C}_y\text{H}_{2y+2})_1$ clusters. Solvent molecules do not interact strongly with each other if they are on opposite sides of the aromatic ring. The AA configuration of $\text{ntpb}(\text{CH}_4)_2$ (fig 3) features one methane molecule centered above the ring and one over the propyl chain. However, the AA configuration of $\text{ntpb}(\text{C}_2\text{H}_6)_2$ has one ethane over the ring and the other displaced considerably in the -X direction presumably due to ethane-ethane interactions (fig 5). The BB configurations of $\text{npb}(\text{C}_y\text{H}_{2y+2})_2$ are in general quite similar (fig 3,5,7) to each other.

The $\text{ngpb}(\text{solvent})_1$ A configurations are missing in the spectral assignments for all three alkane solvents. It is of course possible that these features are hidden under others. However, since the cluster binding energies for the A,B,g,t clusters for a given solvent are so similar, the intensity differences are difficult to explain on the basis of energy considerations. At present we believe the A configurations of the $\text{ngpb}(\text{solvent})_1$ clusters are only present in the beam in small concentrations. In reference 9 we describe the cluster nucleation process

in the beam as occurring through the interaction of solute monomers and solvent dimers or higher clusters. We suggest in this situation that the gA configurations are not kinetically favorable. The AB $\text{ngpb}(\text{solvent})_2$ species may then arise from the gB configuration of $\text{ngpb}(\text{solvent})_1$, which perhaps in some manner alters the formation rate of gA binding.

These observations suggest that the two conformations of the propyl chain in npb have a significant influence on cluster geometry and the effective interactions between the solvent alkane molecules and the aromatic ring. Note, however, that the above conclusion is derived from a calculation in which the propyl chain is held fixed. Nonetheless, the overall cluster geometry should not vary essentially if the propyl chain were released because the experimental data suggest that significant rotational (non librational) motion of the propyl chain can only occur about the $\text{C}_8\text{-C}_9$ band (see below).

B. Cluster Shift.

The binding of two uncharged molecules is typically associated with molecular polarizabilities or dispersion forces.¹⁰ Changes in these interactions upon electronic excitation of one of the molecules gives rise to the cluster red shift. Therefore, the measured cluster shift depends upon the solvent polarizability and changes in the local solute binding site polarizability upon excitation of the solute.

Since there is no direct information on the polarizability of npb in the literature, we assume that it is similar to, but larger than, that of toluene (11.86 \AA^3)¹¹: this larger polarizability would probably result in a larger polarizability change upon electronic excitation. A larger cluster shift is thereby to be expected for a ring centered $\text{ntpb}(\text{CH}_4)_1$ cluster than

for a ring centered toluene $(\text{CH}_4)_1$ cluster. In fact, the observed shifts for $\text{ntp}(\text{CH}_4)_1$ (A configuration) and toluene $(\text{CH}_4)_1$ are -51 cm^{-1} and -44 cm^{-1} , respectively.

In the Results Section a number of origin assignments are made which depend on comparisons between configurations for cluster spectral shifts and published results for simpler systems.² Below we present some detailed discussion which should help to clarify further some of the choices. The solvent/solute interactions are quite different for the A and B configurations of $\text{ntp}(\text{C}_y\text{H}_{2y+2})_1$ (see fig 3,5,7). Potential calculations demonstrate that the effective interaction between the solvent molecule and aromatic π -cloud is significantly larger for the A than the B configuration of ntp . In addition, the calculations yield similar atomic coordinates for the B configurations of both $\text{ngpb}(\text{C}_y\text{H}_{2y+2})_1$ and $\text{ntp}(\text{C}_y\text{H}_{2y+2})_1$ with $y = 2,3$. We have thus assigned, in accordance with previous results,² the larger cluster shifts to the A configurations of $\text{ntp}(\text{C}_y\text{H}_{2y+2})_1$. If the assignments are changed to give smaller spectral shifts to the A configurations and larger ones to the B configurations, comparable large shifts ($\sim 60 \text{ cm}^{-1}$) would be expected for $\text{ngpb}(\text{C}_y\text{H}_{2y+2})_1$ complexes: such shifts are clearly not observed in the spectra. This observation and analysis serve as independent confirmation of the relationship between cluster spectral shift and solute/ π -cloud interaction: solvent molecules create large shifts if they are closely coordinated to the aromatic π -system of the solute.

The cluster shifts for the B configurations of $\text{ngpb}(\text{CH}_4)_1$ and $\text{ntp}(\text{CH}_4)_1$ are -44 and -26 cm^{-1} , respectively. This trend in shifts is primarily associated with the increased interaction of the solvent with the π -system of the aromatic ring and can be in general followed through the series

of systems discussed in this work. Nonetheless, other factors can contribute to the size of the cluster shift. In particular, local solute binding site polarizability can play a role in the overall spectral shift: for example, the $-Z$ component of the molecular polarizability of ngpb is probably larger than the $-Z$ polarizability of ntpb . This consideration would suggest a larger cluster shift for the B configuration of $\text{ngpb}(\text{C}_y\text{H}_{2y+2})_1$ than for the comparable $\text{ntpb}(\text{C}_y\text{H}_{2y+2})_1$ complex even if the effective interaction between the solvent molecule and the π -cloud of the solute were essentially the same. This trend is indeed observed throughout the $\text{npb}(\text{C}_y\text{H}_{2y+2})_1$ series.

Further subtle variations in the $\text{npb}(\text{C}_y\text{H}_{2y+2})_{2,3}$ cluster spectral shift can be found for the case in which two solvent molecules are on the same side of the solute aromatic ring (BB or AA, etc.). In this geometry the two solvent molecules can interact with one another and thereby alter the cluster spectral shift. This effect is most pronounced for solvents of large polarizability such as propane. In fact, a smaller cluster shift is found for the BB configuration of $\text{npb}(\text{C}_3\text{H}_8)_2$ than for $\text{npb}(\text{C}_2\text{H}_6)_2$ or $\text{npb}(\text{CH}_4)_2$.

The cluster shifts of $\text{npb}(\text{C}_y\text{H}_{2y+2})_3$ cannot be readily determined based on the present data. The intense background (see fig 2,4,6) may suggest a number of conformers present in the beam, each contributing to the overall congested intensity pattern.

C. Propyl Chain Motion

As mentioned in the Results Section, two weak features at $37,572.9 \text{ cm}^{-1}$ ($+38.9 \text{ cm}^{-1}$ relative to the $\text{ngpb } 0_0^0$) and 37613.9 cm^{-1} ($+30.7 \text{ cm}^{-1}$ relative to the $\text{ntpb } 0_0^0$) are observed in the 2-color MS spectrum of npb (see fig 1). These two weak features are most likely not due to hot bands

because their relative intensities remain virtually unchanged over a wide range of expansion conditions. We assume then that the two features arise from transitions involving a change in the propyl chain motion. Toluene evidences two such features at 53.5 and 76.5 cm^{-1} due to methyl motion.⁹ The comparison of ngpb, ntpb, and toluene librational frequencies leads one to associate the corresponding motions to CH_3 hindered rotations.

The correlation times for rotations of end groups about bonds 1,2,3 in alkanes are all in the picosecond regime.¹² If relatively free rotation occurs about the phenyl-alkyl ($\text{C}_1\text{-C}_7$, X-axis) or the ethane ($\text{C}_7\text{-C}_8$) bonds, differences between t, g and A,B configurations resulting in sharp spectral features are difficult to understand. In addition, recall that a ring centered ngpb(He)₁ complex is formed but not a ngpb(He)₂ complex^{3a, 13} and that the various configurations of npb(CH₄)₁ have large and different cluster red shifts. These energy differences, line shapes, and apparent stability of the various cluster configurations further suggest that the two weak features at 37572.9 and 37613.9 cm^{-1} are most likely due to the CH_3 rotational or librational motion about the $\text{C}_8\text{-C}_9$ bond. The predicted cluster geometries would thereby remain unaffected by the motion.

V. CONCLUSIONS

The important information that emerges from this study can be summarized as follows:

1. Atom-atom potential calculations provide a viable method for predicting cluster geometry and binding energy for the npb-alkane system. The calculated binding energies for npb(CH₄)₁, npb(C₂H₆)₁, and npb(C₃H₈)₁ are 770 cm^{-1} , 960 cm^{-1} , and 1170 cm^{-1} , respectively. These values are consistent with those obtained by 2-color MS detection methods.

2. The cluster shift is a complex function of solvent polarizability, changes in local binding site polarizability of the solute upon excitation, and solvent/solute and solvent/solvent interactions. In general, however, the cluster shift scales with the effective interaction between the solvent molecules and the π -cloud of the aromatic ring of npb. Similar behavior is observed in the comparable toluene-alkane and benzene-alkane systems.
3. Solvation of npb by simple alkanes has little apparent effect on the geometry of the npb monomer.
4. Motion of the alkane chain is assumed to occur about the C_8-C_9 bond so that only the terminal CH_3 group can rotate within the life time of the excited state (80ns.)

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TABLE I

Atom-Atom potential parameters (see ref. 6)

	A	B	C
	$\frac{\text{cm}^{-1} \text{Å}^6}{\text{mole}}$	$\frac{\text{cm}^{-1}}{\text{mole}}$	Å
Aliphatic-Aliphatic			
C-C	131096.216	8890353.173	3.421
C-H	47829.961	7562708.563	3.940
H-H	15028.103	6390527.943	4.643
Aliphatic-Aromatic			
C-C	162645.059	16520286.388	3.511
C-H	47863.504	6434084.510	3.805
H-H	13070.695	2497532.635	4.192
Aromatic-Aromatic			
C-C	201786.260	30696427.500	3.600
C-H	47897.070	5473891.150	3.670
H-H	11368.240	976080.430	3.740

TABLE II

2-color MS absorption features of $\text{npb}(\text{CH}_4)_x$, $x \leq 3$ near the electronic origin.^a

Energy (vac. cm^{-1})	Energy relative to		Tentative assignment ^b
	cluster 0_0^0 (cm^{-1})	$\text{ntpbb } 0_0^0$ (cm^{-1})	
<u>$\text{npb}(\text{CH}_4)_1$</u>			
37489.7	0	-93.4	$\text{ngpb}(\text{CH}_4) 0_0^0 \text{ B}$ (-44.2 cm^{-1} relative to $\text{ngpb } 0_0^0$)
37523.2	33.5	-59.9	V_0^1
37532.1	0	-51	$\text{ntpbb}(\text{CH}_4) 0_0^0 \text{ A}$
37541.7	9.6	-41.5	X_0^1
37548.1	1.6	-35	Y_0^1
37555.5	23.4	-27.6	V_0^1
37574.5	42.4	- 8.6	V_0^2
<u>$\text{npb}(\text{CH}_4)_2$</u>			
37557	0	-26.1	$\text{ntpbb}(\text{CH}_4) 0_0^0 \text{ B}$
37590.7	33.7	7.6	V_0^1
<u>$\text{npb}(\text{CH}_4)_2$</u>			
37486.7	0	-96.4	$\text{ngpb}(\text{CH}_4)_2 0_0^0 \text{ A B}$ (-47.2 cm^{-1} relative to $\text{ngpb } 0_0^0$)
37501.5	14.8	-81.6	X_0^1
37504.9	18.2	-78.3	Y_0^1
37522.5	35.8	-60.6	V_0^1
37513.1	0	-70	$\text{ntpbb}(\text{CH}_4)_2 0_0^0 \text{ A B}$
37549.6	36.5	-33.5	V_0^1

TABLE II
(continued)

Energy (vac. cm^{-1})	Energy relative to cluster O_0^{O} (cm^{-1})	Energy relative to $\text{ntpbb O}_0^{\text{O}}$ (cm^{-1})	Tentative assignment ^b
37524.5	0	-58.6	$\text{ntpbb}(\text{CH}_4)_2 \text{O}_0^{\text{O}}$ A A
37537.1	12.6	-46	X_0^1
37541.9	17.4	-41.2	Y_0^1
37551.6	27.1	-31.5	V_0^1
37572	47.5	-11	V_0^2
37546.9	0	-36.2	$\text{ntpbb}(\text{CH}_4)_2 \text{O}_0^{\text{O}}$ B B
37559.4	12.5	-23.8	X_0^1
37565.4	18.5	-17.7	Y_0^1
37584.5	37.6	1.4	V_0^1
<u>$\text{npbb}(\text{CH}_4)_3$</u>			
37479.8	0	-103.3	$\text{ngppb}(\text{CH}_4)_3 \text{O}_0^{\text{O}}$ A B B (-054.1 cm^{-1} relative to $\text{ngpb O}_0^{\text{O}}$)
37505.5	0	-77.6	$\text{ntpbb}(\text{CH}_4)_3 \text{O}_0^{\text{O}}$ A B B

a) The cluster O_0^{O} of the lowest electronic energy is tabulated first together with its vdW modes, followed by the next lowest electronic energy cluster O_0^{O} and its vdW modes. Therefore, the tabulated features are not necessarily in order of ascending energy.

b) X, Y denote vdW bending motions and V stands for vdW stretch. A (above with chain) and B (below, away from chain) refer to configurations of the solvent relative to the solute propyl chain position with respect to the ring plane. See text for explanation.

TABLE III

2-color MS absorption features of $\text{npb}(\text{C}_2\text{H}_6)_x$ $x \leq 3$ near the electronic origin^a.

Energy (vac cm^{-1})	Energy relative to		Tentative assignment ^b
	cluster 0_0^0 (cm^{-1})	$\text{ntpbb } 0_0^0$ (cm^{-1})	
<u>$\text{npb}(\text{C}_2\text{H}_6)_1$</u>			
37502.5	0	-80.6	$\text{ngpb}(\text{C}_2\text{H}_6) 0_0^0$ B (-31.4 cm^{-1} relative to $\text{ngpb } 0_0^0$)
37524.9	22.4	-58.3	V_0^1
37520.3	0	-62.8	$\text{ntpbb}(\text{C}_2\text{H}_6) 0_0^0$ A
37531.6	11.3	-51.6	X_0^1
37540.3	20.0	-42.8	Y_0^1
37550.3	30.0	-32.9	V_0^1
37556.8	0	-26.3	$\text{ntpbb}(\text{C}_2\text{H}_6) 0_0^0$ B
37565.1	8.3	-18	X_0^1
37571.2	14.4	-11.9	Y_0^1
37579.9	23.1	-3.2	V_0^1
37596.3	39.5	13.2	V_0^2
<u>$\text{npb}(\text{C}_2\text{H}_6)_2$</u>			
37486.4	0	-96.7	$\text{ngpb}(\text{C}_2\text{H}_6)_2 0_0^0$ BB (-47.6 cm^{-1} relative to $\text{ngpb } 0_0^0$)
37494.6	8.2	-88.5	X_0^1
37506.2	19.8	-76.9	V_0^1

TABLE III
(continued)

Energy relative to Energy relative to Tentative assignment^b

(vac cm⁻¹) cluster 0₀⁰ (cm⁻¹) ntpb 0₀⁰ (cm⁻¹)

37498	0	-85.2	ntpb(C ₂ H ₆) ₂ 0 ₀ ⁰ A B
37519.1	21.1	-64	v ₀ ¹
37524.7	0	-58.4	ntpb(C ₂ H ₆) ₂ 0 ₀ ⁰ A A
37555.5	30.8	-27.6	v ₀ ¹
37580.6	55.9	- 2.5	v ₀ ²
37534.4	0	-48.7	ntpb(C ₂ H ₆) ₂ 0 ₀ ⁰ B B
37544	9.6	-39.1	x ₀ ¹
37551.1	16.7	-32	y ₀ ¹
37555.5	21.	-27.6	v ₀ ¹
37570.8	36.4	-12.3	v ₀ ²
<u>ntpb(C₂H₆)₃</u>			
37490.6		-92.6	
37500.5		-82.6	
37512.6		-70.6	
37519.8		-63.3	
37528.7		-54.4	
37535.6		-47.5	
37548.1		-35	
37555.5		-27.6	
37562.1		-21.1	
37570.7		-12.5	
37577.1		- 6.1	
37585.5		2.4	

a, b: See footnotes for Table 2

TABLE IV

2-color MS absorption features of $\text{npb}(\text{C}_3\text{H}_8)_x$, $x \leq 5$ near the electronic origin^a.

Energy (vac. cm^{-1})	Energy relative to cluster O_0^0 (cm^{-1})	Energy relative to $\text{ntp}(\text{C}_3\text{H}_8)_0^0$ (cm^{-1})	Tentative assignment ^b	
<u>$\text{npb}(\text{C}_3\text{H}_8)_1$</u>				
37509.1	0	-74.1	$\text{ngpb}(\text{C}_3\text{H}_8)_1 \text{O}_0^0 \text{ B}$	(-24.9 cm^{-1} relative to $\text{ngpb} \text{O}_0^0$)
37528.1	19	-55	V_0^1	
37543.	34.9	-40.1	V_0^2	
37550.9	0	-52.2	$\text{ntp}(\text{C}_3\text{H}_8)_1 \text{O}_0^0 \text{ A}$	
37547.1	16.2	-36.1	X_0^1	
37550.1	19.2	-35	Y_0^1	
37555.5	22.4	-29.8	V_0^1	
37570.8	39.9	-12.3	V_0^2	
<u>$\text{npb}(\text{C}_3\text{H}_8)_2$</u>				
37566.3	0	-16.9	$\text{ntp}(\text{C}_3\text{H}_8)_1 \text{O}_0^0 \text{ B}$	
37573.7	7.4	- 9.4	X_0^1	
37578.4	12.1	- 4.7	Y_0^1	
37586.5	20.2	5.4	V_0^1	
37502	0	-81.1	$\text{ngpb}(\text{C}_3\text{H}_8)_2 \text{O}_0^0 \text{ B B}$	(-32 cm^{-1} relative to $\text{ngpb} \text{O}_0^0$)
37511.2	9.2	-71.9	X_0^1	
37523.7	21.7	-59.5	V_0^1	

TABLE IV
(continued)

Energy (vac. cm^{-1})	Energy relative to cluster 0_0^0 (cm^{-1})	Energy relative to $\text{ntpb } 0_0^0$ (cm^{-1})	Tentative assignment ^b
37507.4	0	-75.8	$\text{ngpb}(\text{C}_3\text{H}_8)_2 0_0^0$ A B (-26.6 cm^{-1} relative to $\text{ngpb } 0_0^0$)
37518.6	11.2	-64.5	x_0^1
37528.6	21.2	-54.6	v_0^1
37514.6	0	-68.5	$\text{ntpb}(\text{C}_3\text{H}_8)_2 0_0^0$ A B
37522.9	18.3	-50.2	v_0^1
37554.3	0	-28.8	$\text{ntpb}(\text{C}_3\text{H}_8)_2 0_0^0$ B B
37561.4	7.1	-21.7	x_0^1
37568.5	14.1	-14.7	v_0^1
<u>$\text{ntpb}(\text{C}_3\text{H}_8)_3$</u>			
37441.8		-141.4	
37461.2		-121.9	
37468.9		-114.2	
37481		-102.1	
37492		- 91	
37512		- 71	
37517.1		- 66	
37528.1		- 55	
37535.6		- 47.5	
37547.7		- 35.4	
37556.5		- 26.6	
37565.9		- 17.2	
37574.9		- 8.2	

a, b: See footnotes for Table 2

FIGURE CAPTIONS

FIGURE 1.

2-color MS spectrum of npb at the 0_0^0 . The electronic origins for ngpb and ntpb are observed at 37533.9 cm^{-1} and 37583.1 , respectively. Experimental conditions : 0.5mm pulsed nozzle operated at 10Hz; nozzle temperature = 25°C , backing pressure $P_0 = 100 \text{ psi}$, ionization wavelength = 3050A.

FIGURE 2.

2-color MS spectra of $\text{npb}(\text{CH}_4)_x$, $x \leq 3$ observed at the 0_0^0 with 2% CH_4 in the expansion with helium carrier gas. Intensity scale is different for each cluster. The energy scale is relative to the ntpb 0_0^0 at 37583.1 cm^{-1} . Dotted lines indicate the 0_0^0 of ngpb (lower energy) and ntpb. Experimental conditions: see figure 1.

FIGURE 3

Minimum energy configurations of $\text{npb}(\text{CH}_4)_x$, $x \leq 2$ as obtained from potential calculation. The order of the cluster configurations is arranged according to Table 2.

t,B: indicates the solvent alkane molecule binds below the aromatic ring of ntpb.

g,AB: indicates the solvent alkane molecules bind above and below the aromatic ring of ngpb.

"Above the ring" refers to the side of the ring (+Z direction) with the propyl chain and "below the ring" (-Z direction) refers to the side of the ring without the propyl. The propyl chain extends in the +X direction. The atomic coordinates of the methane molecule in g, A are identical to those of the methane molecule binding above the aromatic ring in g, AB. Detailed atomic coordinates of the clusters can be provided upon request.

FIGURE 4

2-color MS spectra of $\text{npb}(\text{C}_2\text{H}_6)_x$, $x \leq 3$ observed at the 0_0^0 with 2% C_2H_6 in the expansion with helium carrier gas. The intensity scale is different for each cluster. Experimental conditions: see figure 1.

FIGURE 5

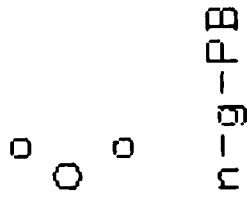
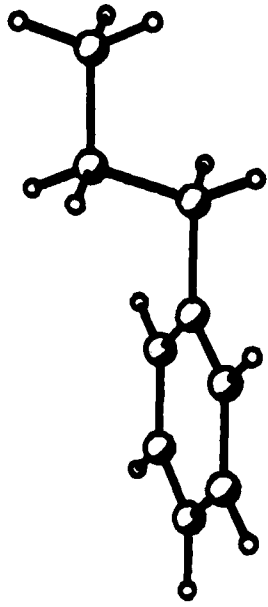
Minimum energy configurations of $\text{npb}(\text{C}_2\text{H}_6)_x$, $x \leq 2$ obtained from potential calculations. The order of the configurations is arranged according to Table 3. Detailed atomic coordinates of the clusters can be provided upon request.

FIGURE 6

2-color MS spectra of the $\text{npb}(\text{C}_3\text{H}_8)_x$, $x \leq 3$ observed at the 0_0^0 with 2% C_3H_8 in the expansion with helium carrier gas. Intensity scale is different for each cluster. Experimental conditions: see figure 1.

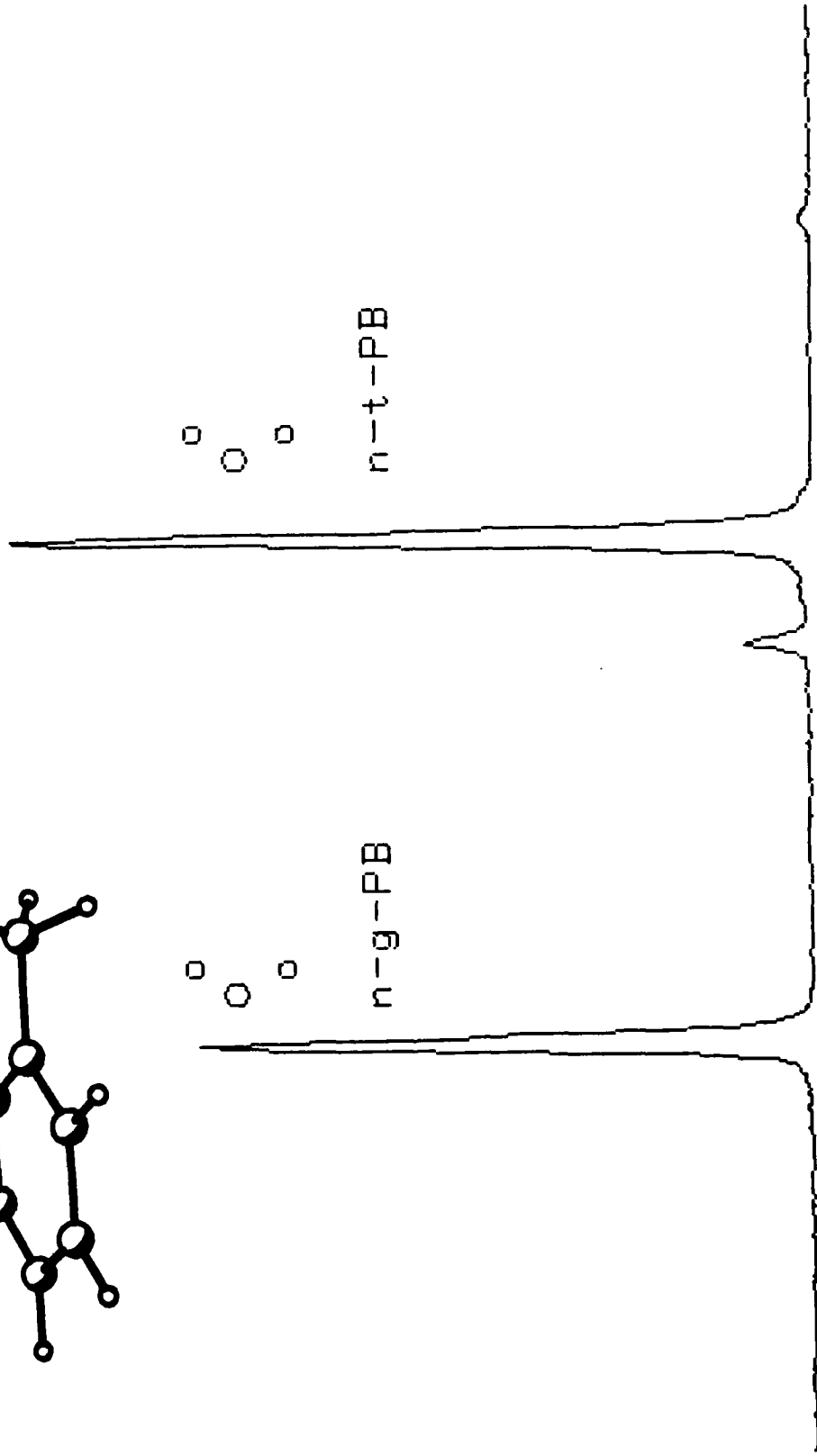
FIGURE 7

Minimum energy configurations of $\text{npb}(\text{C}_3\text{H}_8)_x$, $x \leq 2$ obtained from potential calculations. The order of the configurations is arranged according to Table 4. Detailed atomic coordinates of the clusters can be provided upon request.



n-t-PB

n-g-PB



37503

37543

37583

37623

ENERGY (CM⁻¹)

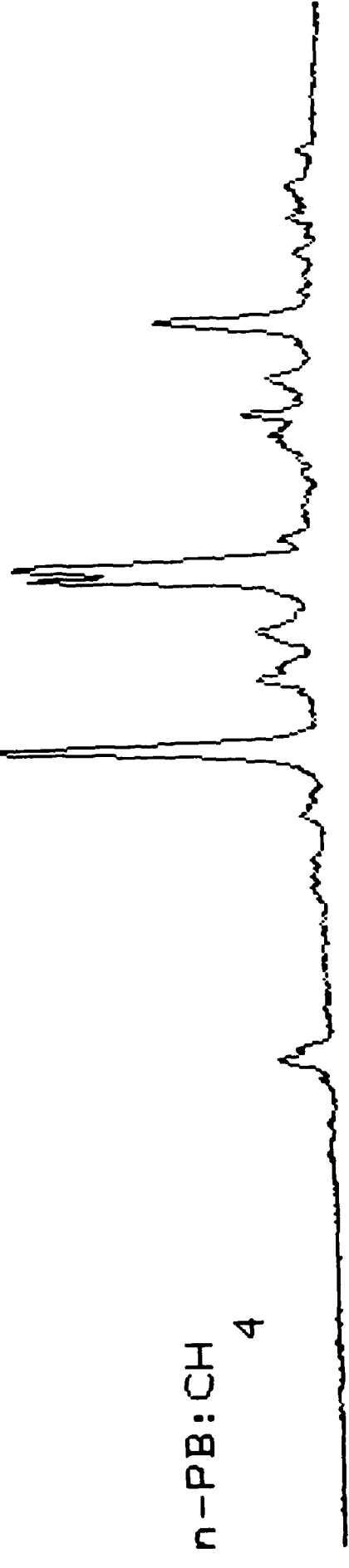
n-PB: (CH)
4 3



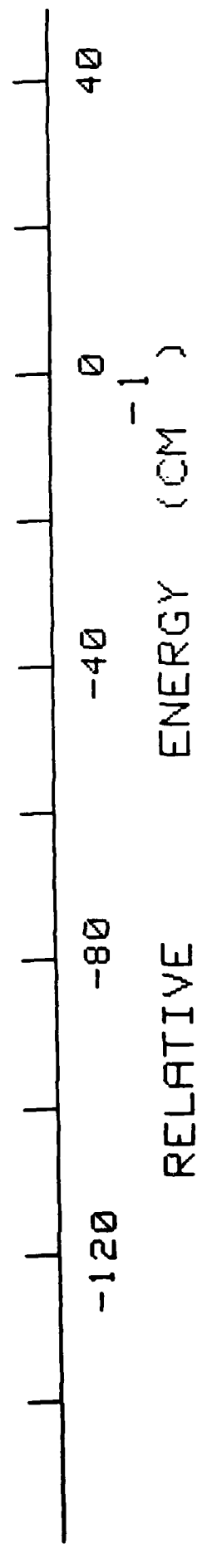
n-PB: (CH)
4 2



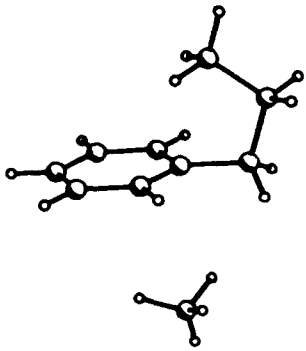
n-PB: CH
4



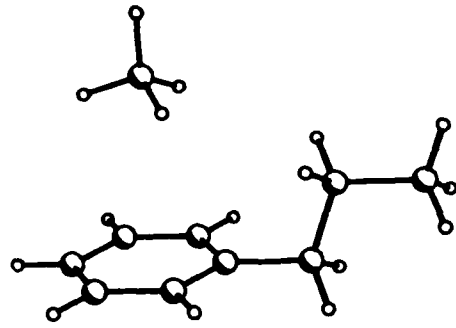
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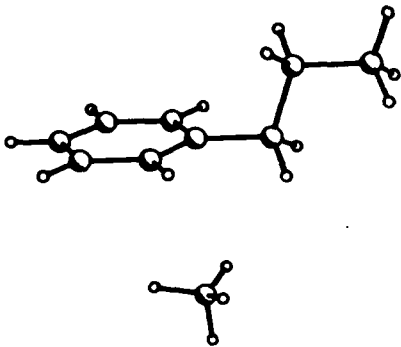
g, B



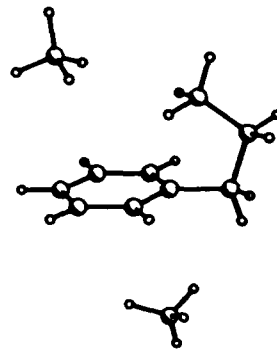
t, A



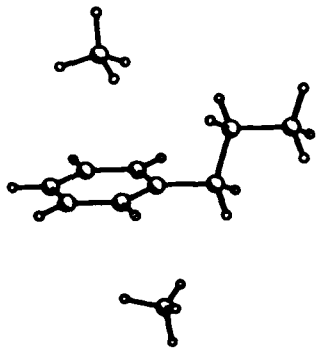
t, B



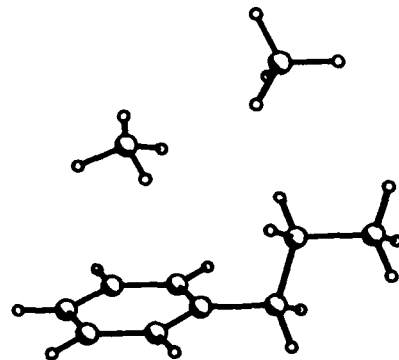
g, AB



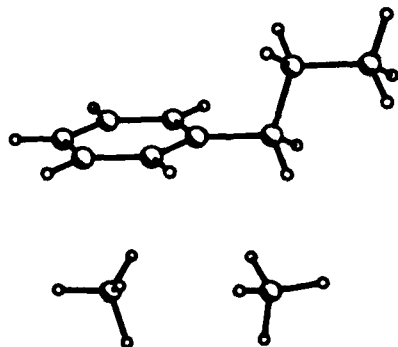
t, AB



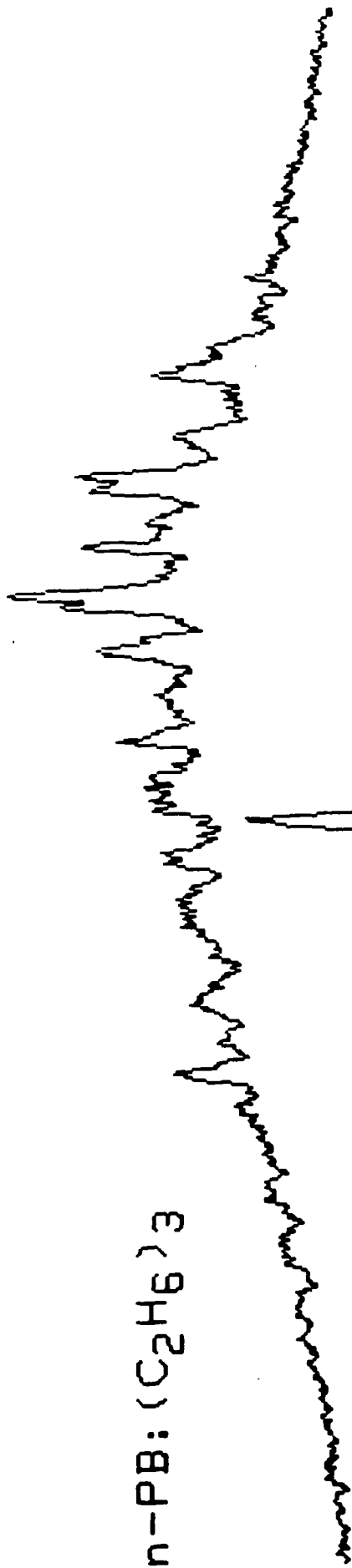
t, AA



t, BB



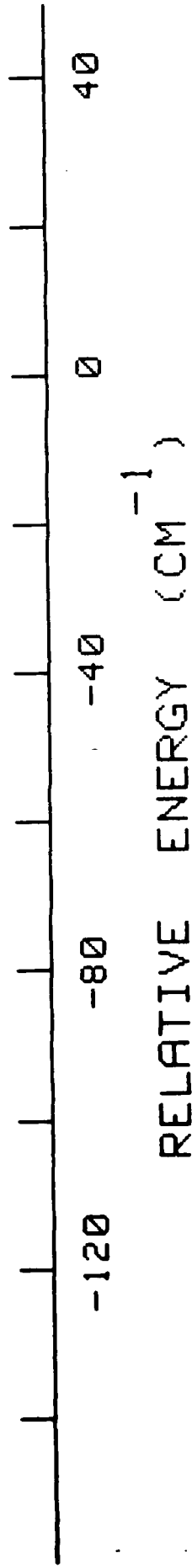
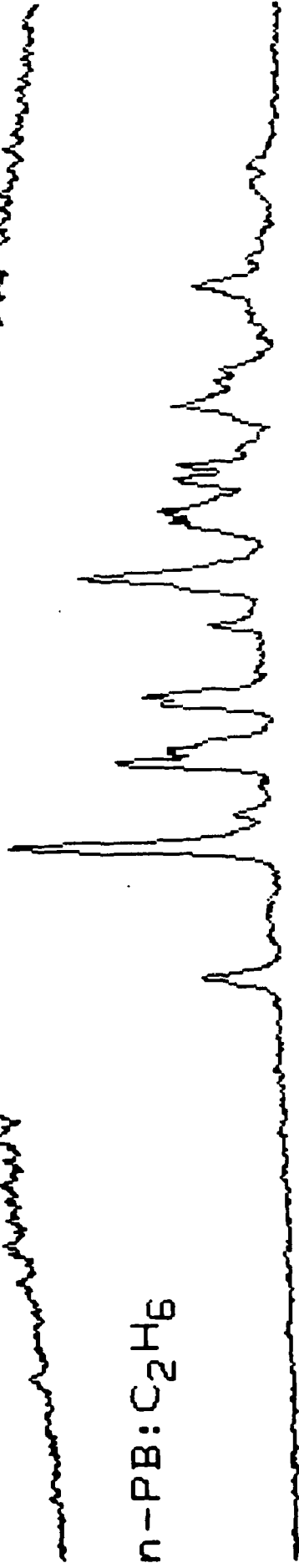
n-PB: (C₂H₆)₃

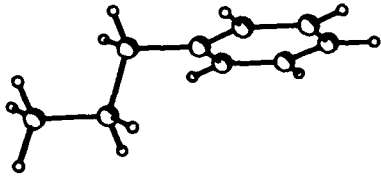
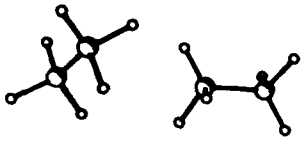


n-PB: (C₂H₆)₂

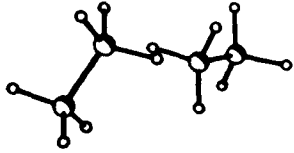
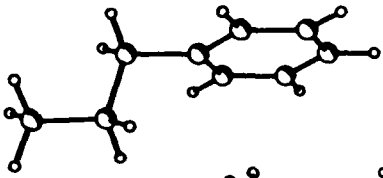


n-PB: C₂H₆

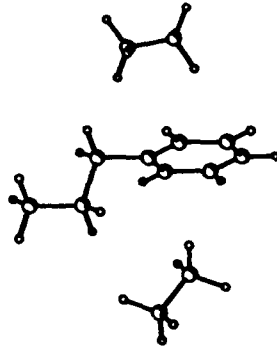




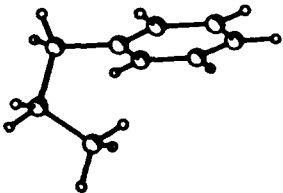
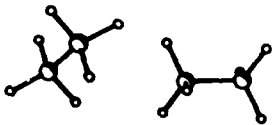
t, BB



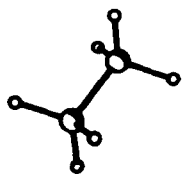
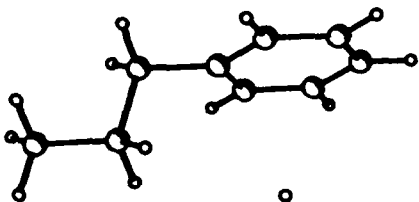
t, BA



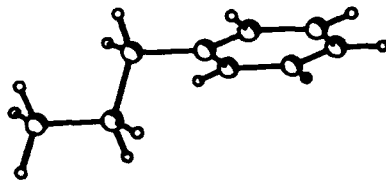
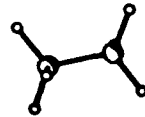
t, AB



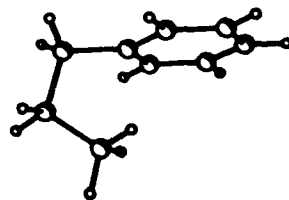
g, BB



t, A

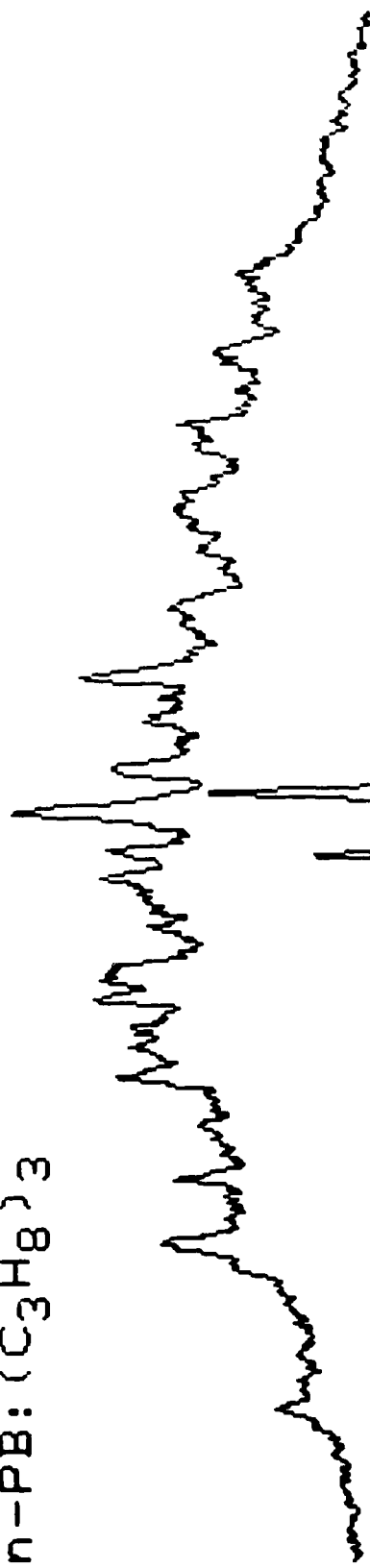


t, B



g, B

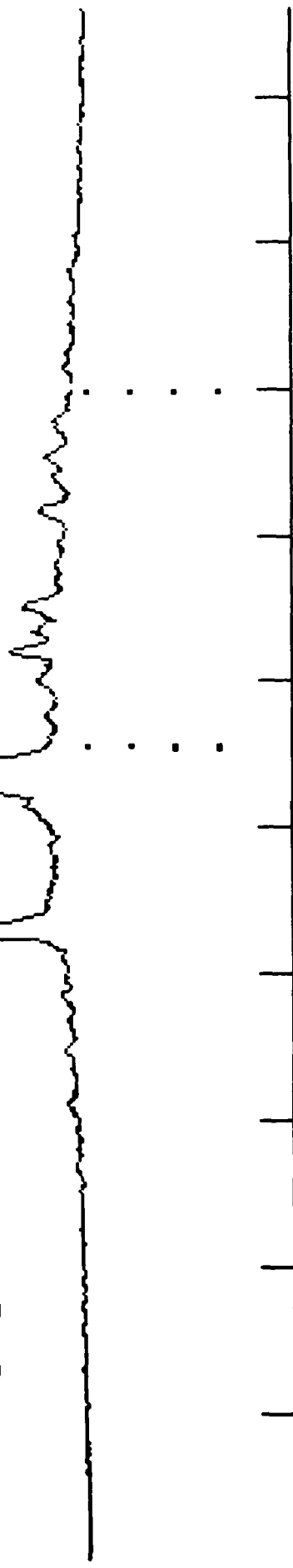
n-PB: (C₃H₈)₃



n-PB: (C₃H₈)₂



n-PB: C₃H₈



-120

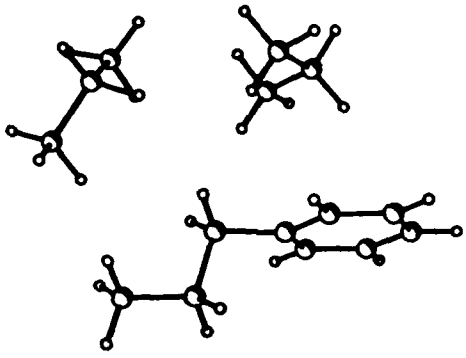
-80

-40

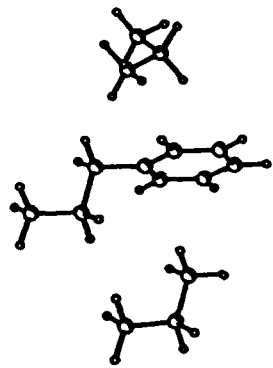
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40

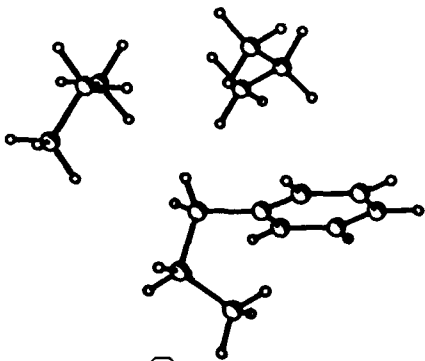
RELATIVE ENERGY (CM⁻¹)



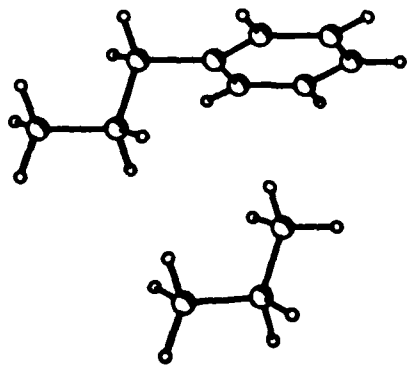
t, BB



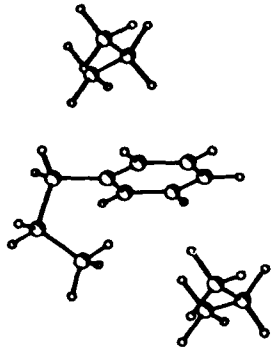
t, RB



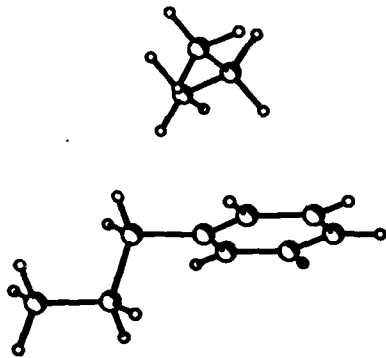
g, BB



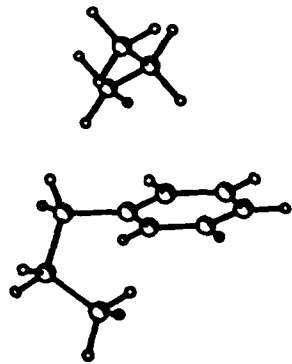
t, A



g, RB

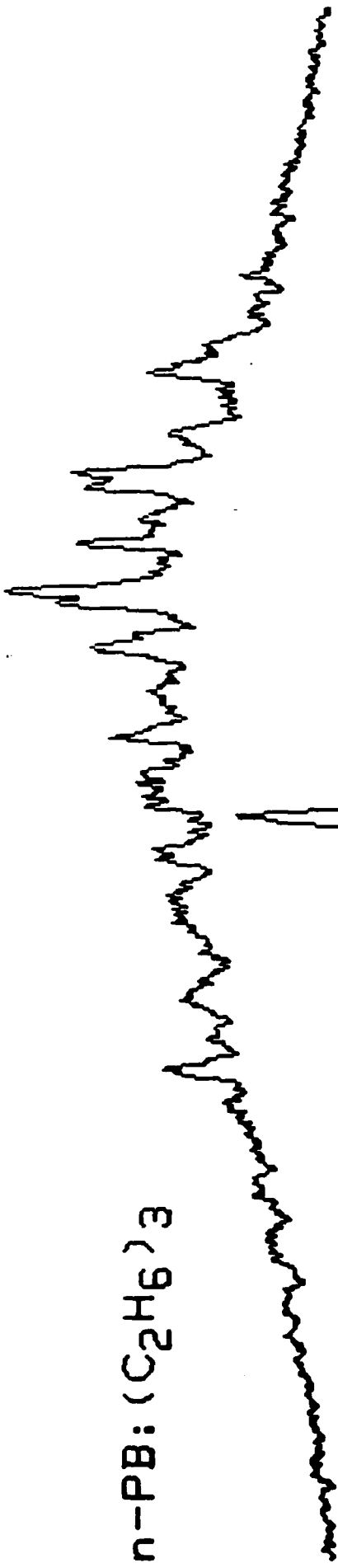


t, B



g, B

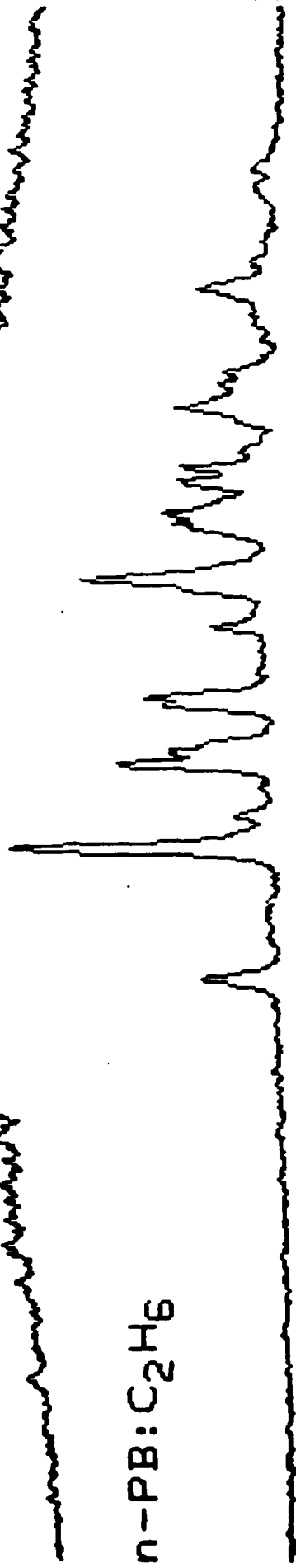
n-PB: (C₂H₆)₃



n-PB: (C₂H₆)₂

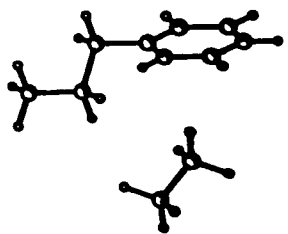


n-PB: C₂H₆

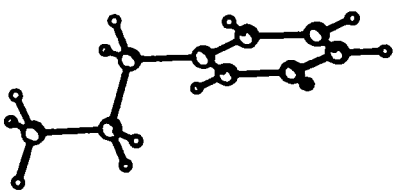
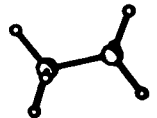


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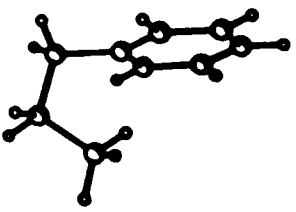




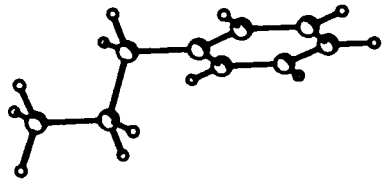
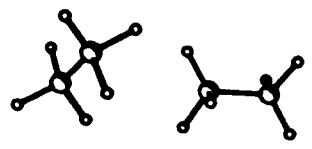
t, AB



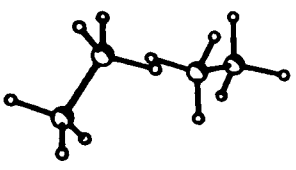
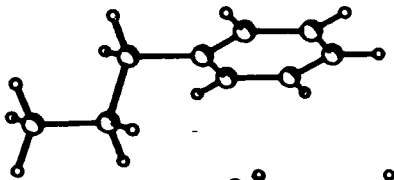
t, B



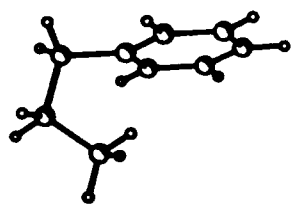
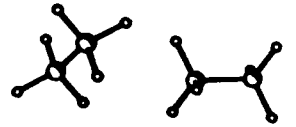
g, B



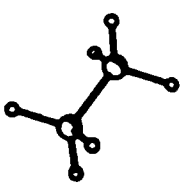
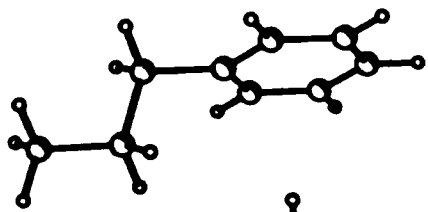
t, BB



t, AA



g, BB

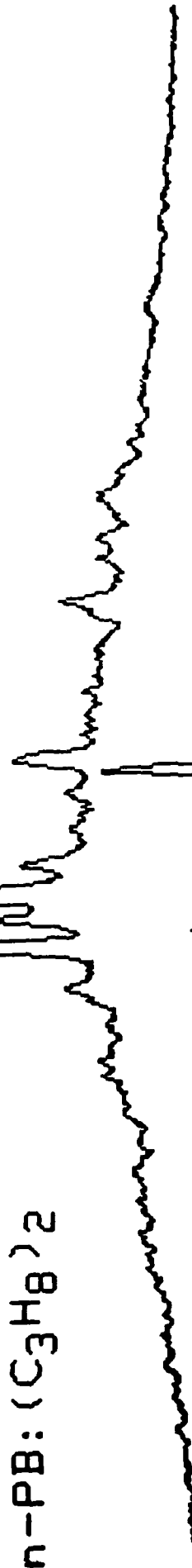


t, B

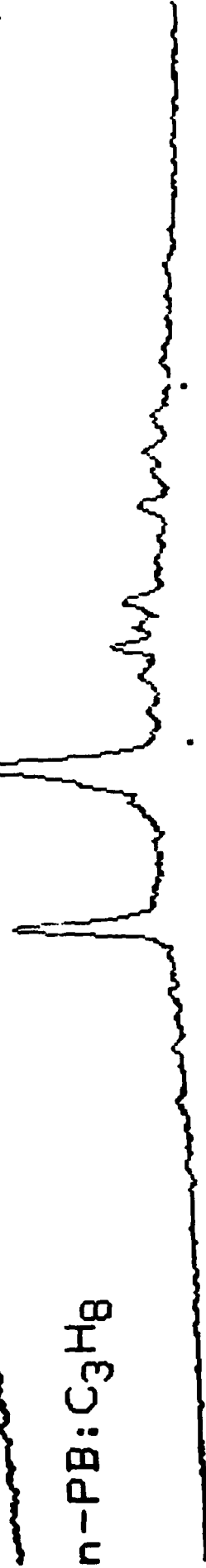
n-PB: (C₃H₈)₃



n-PB: (C₃H₈)₂

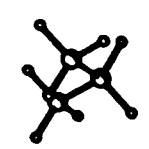
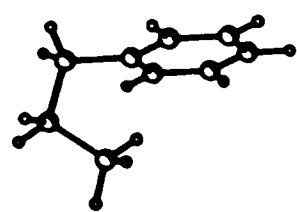


n-PB: C₃H₈

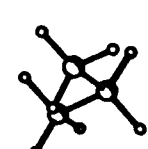
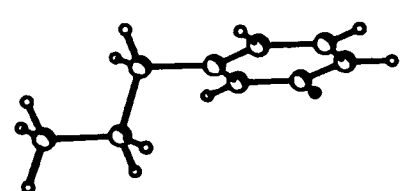


RELATIVE ENERGY (CM⁻¹)

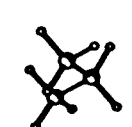
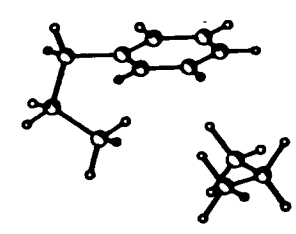
g, B



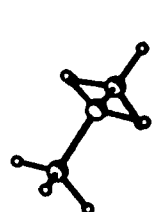
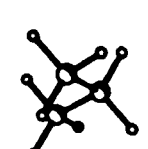
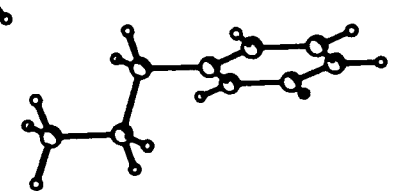
t, B



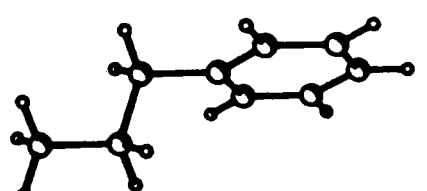
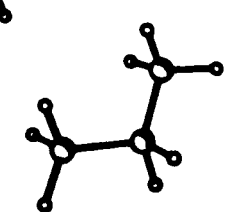
g, AB



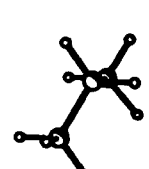
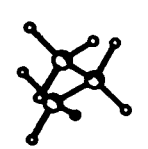
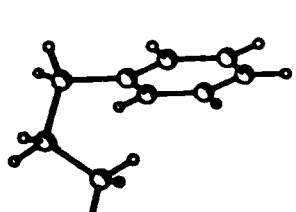
t, BB



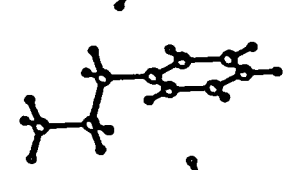
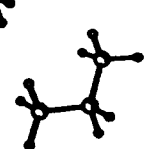
t, D



g, BB



t, AB



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