Lawrence Berkeley National Laboratory

Recent Work

Title

HIGHLY-RESOLVED SPECTRA OF LOCAL MODES OF BENZENE

Permalink

<https://escholarship.org/uc/item/92f9d6pb>

Authors

Page, R.H.

Shen, Y.R.

Lee, Y.T.

Publication Date

1987-07-01

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Materials & Chemical Sciences Division

RECEIVED
LAWRENCE
BERKELEY LABORATORY

SEP 18 1987

Submitted to Physical Review Letters

LIBRARY AND
DOCUMENTS SECTION

HIGHLY-RESOLVED SPECTRA OF LOCAL MODES OF BENZENE

R.H. Page, Y.R. Shen, and Y.T. Lee

July 1987

For Reference

Not to be taken from this room

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Submitted to Physical Review Letters
PACS 33.20 Ea, 33.70 Jg, 33.40 Ta

HIGHLY-RESOLVED SPECTRA OF LOCAL MODES OF BENZENE

Ralph H. Page,^{*(a)} Y. R. Shen,^{*} and Y. T. Lee[†]

Materials and Chemical Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720 USA

ABSTRACT

Rotational cooling by supersonic expansion and laser labelling spectroscopy were used to obtain high-resolution fundamental and first and second overtone spectra of C-H stretches of benzene in a molecular beam. Rich fine structure in the spectra has been observed. Transformation from the "normal mode" picture to the "local mode" picture seems to occur between $v = 2$ and $v = 3$. Vibrational lifetimes in local mode bands exceed ~ 0.5 psec.

The familiar normal mode (NM) picture describes well the small-amplitude molecular vibrations at low vibrational excitations. But as the vibrational energy is raised, the density of vibrational states increases rapidly, and anharmonic couplings between normal modes become important; the normal mode picture then ceases to provide a good description of the vibrational motion. It was found, however, that for some molecules even at relatively high vibrational energies (10,000-25,000 cm^{-1}), there still exist well-defined peaks in the vibrational spectrum. They were identified as overtone vibrations confined largely to single bonds, for example, a C-H stretch. Such vibrations localized to single bonds are often known as local modes.^{1,2}

Treated as diatomic vibrations, the energy levels of a local mode (LM) can be easily calculated.^{1,2} Couplings between the LM and other modes, however, add fine structure to the LM spectrum. For a better understanding of high excited molecular vibrations, we would like to know how the vibrational spectrum changes from the NM to the LM picture as the vibrational energy increases. For small molecules, such as methane,³ the spectra remain well resolved in the transformation from NM to LM. A few combination states of NM are nearly degenerate with the LM states; the couplings are weak and the spectral lines in a LM manifold are very sharp, corresponding to a lifetime more than 1 nsec. Larger molecules, with a much larger density of NM combination states interacting with the LM states, appear to have much broader LM spectral lines. Reported measurements on the C-H stretches of benzene showed that even in the transformation from NM to LM, the successive overtones seem to be always fairly broad, with widths in the tens of cm^{-1} .⁴ We wonder whether the observed widths were the results of poor spectral

resolution or actual lifetime broadening. In the former case, we could hope to improve the resolution and observe the fine structure; we could then obtain more information on the transition behavior from NM to LM.

In this paper, we show that with the help of supersonic cooling of molecules and the nonlinear labelling spectroscopic technique,⁵ it is indeed possible to obtain high-resolution vibrational spectra for the C-H stretches of benzene from $v = 1$ to $v = 3$. Fine structures with a resolution of $\sim 1 \text{ cm}^{-1}$ have been observed in the spectra.

The normal vibrational modes of benzene in the ground electronic state are fairly well known.⁶ There is a famous case of Fermi resonance between the C-H stretch ν_{20} and the combination modes $\nu_8 + \nu_{19}$ and $\nu_1 + \nu_6 + \nu_{19}$. This should yield three peaks around ν_{20} in the $v = 1$ spectrum. At finite temperatures, however, hot-band transitions and rotational sidebands smear the peaks and make the spectral lines appear much broader. For higher overtones ($v \geq 2$), more combination states are supposed to be nearly degenerate with the C-H stretch, and one expects to find more peaks in the spectrum sharing the oscillator strength of the C-H vibration. But if the LM character of the C-H stretch now dominates, the coupling between the C-H stretch and the nearly degenerate combination states will diminish, and the spread of oscillator strength to those combination states will be limited. In either case, the overtone spectrum can also be significantly broadened by the hot-band transitions and rotational sidebands at finite temperatures.

In order to reduce spectral congestion due to rotational sidebands and hot-band transitions, we used in our experiment the state-selective labelling spectroscopic technique⁵ on a supersonic beam of benzene.

The supersonic expansion of the benzene-seeded argon gas resulted in a rotational cooling of benzene to $T_{\text{rot}} \sim 5^\circ\text{K}$. This reduced the width of the rotational envelope of each vibrational transition ($\propto \sqrt{T_{\text{rot}}}$) from the room-temperature value of 30 cm^{-1} to 4 cm^{-1} . The remaining hot-band transitions were further removed by the use of three-level state-selective spectroscopy, schematically shown in Fig. 1(a). Resonant two-photon ionization (R2PI) via the 38608-cm^{-1} $\tilde{A} \leftarrow \tilde{X}$ 6_0^1 transition⁷ was used to monitor the population of a particular rotational state (or a set of a few rotational states) of the ground vibrational state. If a certain excitation depleted this population, the ionization signal would drop. Thus, by scanning the IR pump laser over the overtone transitions, we could obtain a state-selective overtone rotation-vibration spectrum. The UV and IR beams were generated by frequency conversion in nonlinear crystals with Nd:YAG laser-pumped dye lasers. They had linewidths 0.3 and 1 cm^{-1} , respectively. Details of the experimental setup will be reported elsewhere.⁸

Figure 1(b,c) shows the $\tilde{A} \leftarrow \tilde{X}$ 6_0^1 absorption spectrum of benzene obtained from R2PI and its theoretical fit using $T = 5^\circ\text{K}$. The P, Q, and R rotational branches are well resolved in the spectrum. Since the rotational transitions are heavily bunched in the Q branch, a UV excitation in the Q branch with a 0.3 cm^{-1} resolution effectively probes the population of many rotational states of the ground vibrational manifold. On the other hand, excitation in the P (or R) branch farther in the wing probes only a few selected rotational states. Thus, by fixing the UV probe frequency in the Q branch, and tuning the IR pump beam over the vibrational excitations, we obtained the rotationally less selective overtone spectra ($v = 1-3$) of the C-H

stretches shown in Fig. 2. More highly resolved spectra could be obtained by setting the UV probe frequency in the wing of the P branch, but we shall postpone their presentation to a later publication,⁸ as they are not needed for the present discussion. In Fig. 3, we reproduce, for comparison, the corresponding room-temperature spectra ($v = 1-9$) measured by Reddy et al.⁴ in a benzene gas cell.

Figure 2(a) gives the $v = 1$ spectrum, with the three peaks expected from the aforementioned Fermi resonance clearly resolved. Comparison of this spectrum with the corresponding room-temperature one in Fig. 3(a) shows how drastically rotational cooling and hot-band suppression by labelling spectroscopy have clarified the spectrum. Each peak in Fig. 2(a) has a width of 4 cm^{-1} arising from the residual rotational envelope. The $v = 2$ spectrum is given in Fig. 2(b). It is characterized by more than 20 peaks spread over a relatively broad spectral range of $\sim 200\text{ cm}^{-1}$, each again having a rotational envelope width of 4 cm^{-1} . These peaks correspond to different vibrational transitions in the 6007 cm^{-1} region. In the $v = 3$ spectrum of Fig. 2(c), four peaks can be discerned, but the one at 8827 cm^{-1} clearly dominates. Two characteristic features are noted in this spectrum. First, the peaks spread over a spectral range appreciably narrower than that of $v = 2$. Second, the strong peak at 8827 cm^{-1} has a width of 10 cm^{-1} instead of 4 cm^{-1} , suggesting either an overlap of several vibrational transitions or an appreciable increase of the homogeneous broadening. Our more detailed spectra⁸ show that the former is the case.

The results of Fig. 2 indicate a characteristic change in the nature of the vibrational spectra between $v = 2$ and $v = 3$, presumably

due to the change from NM to LM in the description of the overtone vibrational states. With increasing vibrational excitation, the density of combination states grows rapidly. If the coupling of the C-H stretch with the combination modes remained unchanged (i.e., the C-H stretch did not become more localized), then with increasing v , the C-H stretching overtone spectrum would turn into a band with a rapidly growing overall width and number of peaks. While the $v = 2$ spectrum relative to the $v = 1$ spectrum in Fig. 2 does indeed appear this way, the $v = 3$ spectrum certainly behaves differently. It has clearly a narrower frequency spread with far fewer significant peaks than the $v = 2$ spectrum. Most of the oscillator strength shows up in a single peak. All these are indications that the C-H stretch has become "localized" at $v = 3$; the coupling between the C-H stretch and other modes has decreased significantly.

We can use a simple perturbation calculation to estimate the average coupling strength S between the C-H stretch and the nearly degenerate combination states. From the separations of the three peaks in Fig. 2(a), we find $S \sim 25 \text{ cm}^{-1}$ for $v = 1$. For C-H vibrations at $v = 2$ and 3, the nearly degenerate combination states form a quasi-continuum with a density of states ρ that can be estimated by, for example, the Whitten-Rabinovitch (WR) approximation.⁹ The overall spectral widths of the overtone bands are given by $\Gamma \sim (2\pi/\hbar^2)|S|^2\rho$. For $v = 2$, we obtain $\Gamma \sim 30 \text{ cm}^{-1}$ from Fig. 2(b), $\rho \sim 10^3/\text{cm}^{-1}$, and hence, $S \sim .07 \text{ cm}^{-1}$. For $v = 3$, we have $\Gamma \sim 10 \text{ cm}^{-1}$, $\rho \sim 10^5/\text{cm}^{-1}$,¹⁰ and $S \sim .004 \text{ cm}^{-1}$. The result here shows that the coupling strength S indeed decreases very rapidly as v changes from 1 to 3.

The picture deduced from our spectra differs from that of Ref. 4:

we find that the LM bands contain many fine structures and the LM band envelopes are much narrower than was previously thought.

We expect that the C-H stretch would become increasingly localized with larger v so that the overtone bandwidth for $v > 3$ is not likely to be significantly larger than the 10 cm^{-1} width of the $v = 3$ band. Unfortunately, because of laser limitations, our state-selective spectroscopic technique is not sensitive enough to obtain overtone spectra with $v > 3$. Sibert et al.¹¹ have calculated higher C-H overtone spectra ($v = 5-9$) of benzene, and found an apparent bandwidth of $\sim 50\text{ cm}^{-1}$, in agreement with the room-temperature experimental result of Ref. 4. This is, however, much larger than the $\sim 10\text{ cm}^{-1}$ width we would expect. It would certainly be interesting if the same calculation on the $v = 1-4$ bands could be done.

We have reported here a high-resolution study of how a vibrational mode of a typical large molecule changes its character from normal-mode to local-mode with increasing excitation energy. This was made possible by using a state-selective nonlinear spectroscopic technique on a rotationally cooled molecular beam. The results indicate that the local-mode feature of the C-H stretch of benzene begins to prevail at vibrational excitations between $v = 2$ and $v = 3$. The homogeneous linewidth of the local-mode spectra is not likely to exceed 10 cm^{-1} , suggesting a vibrational lifetime longer than 0.5 psec.

We thank the San Francisco Laser Center for the loan of some equipment used in this experiment. This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

References

(a) Present address: IBM Almaden Research Center, 650 Harry Rd., San Jose, CA 95120-6099.

* Also associated with Department of Physics, University of California, Berkeley.

† Also associated with Department of Chemistry, University of California, Berkeley.

1. M. S. Child and L. Halonen, Adv. Chem. Phys. 57, 1 (1984), and references therein.
2. M. L. Sage and J. Jortner, Adv. Chem. Phys. 47, part I, 293 (1981), and references therein.
3. J. W. Perry, D. J. Moll, A. Kuppermann, and A. H. Zewail, J. Chem. Phys. 82, 1195 (1985), and references therein.
4. K. V. Reddy, D. F. Heller, and M. J. Berry, J. Chem. Phys. 76, 2814 (1982).
5. Y. R. Shen, The Principles of Nonlinear Optics (Wiley, New York, 1984), p. 227.
6. E. B. Wilson, Jr., J. C. Decius, and P. C. Cross, Molecular Vibrations (McGraw-Hill, New York, 1955).
7. J. H. Callomon, T. M. Dunn, and I. M. Mills, Phil. Trans. Roy. Soc. London, Ser. A 259, 499 (1966).
8. R. H. Page, Y. T. Lee, and Y. R. Shen, to be published.
9. G. Z. Whitten and B. S. Rabinovitch, J. Chem. Phys. 38, 2466 (1963); 41, 1883 (1964).
10. R. G. Bray and M. J. Berry, J. Chem. Phys. 71, 4909 (1979).
11. E. L. Sibert III, W. B. Reinhardt, and J. T. Hynes, J. Chem. Phys. 81, 1115 (1984), and references therein.

Figure Captions

Fig. 1 (a) Double resonance, three level saturation spectroscopy scheme. Vibrational-ground-state molecules in selected rotational states are probes with resonantly-enhanced two-photon ionization (R2PI) via the $\bar{A} + \bar{X} 6_0^1$ transition. IR overtone transitions diminish the ground state (probe) population and hence the ion signal. Hot-band transitions are suppressed. (b) 6_0^1 band R2PI spectrum showing P ($\Delta J = -1$), Q ($\Delta J = 0$), and R ($\Delta J = +1$) branches. (c) Simulated 6_0^1 spectrum with $T_{\text{rot}} = 5^\circ\text{K}$.

Fig. 2 Nonselective (Q branch probe) spectra of $v = 1, 2$, and 3 bands. Absorption is in arbitrary units; error bars indicate the noise level. Band centers are marked at 3079 , 6007 , and 8827 cm^{-1} . "Localization" is evident in the spectra as v increases from 1 to 3 .

Fig. 3 Local mode absorption spectra of room temperature benzene gas, obtained with $\sim 1 \text{ cm}^{-1}$ resolution by Reddy et al. in Ref. 4. In each panel, the C-H stretching quantum number and band center frequency appear at the upper right, and horizontal arrows mark FWHM linewidths.

Implementation of three-level saturation spectroscopy

XBL 872-6149

Benzene monomer nonselective spectra

XBL-872-6146

Room temperature absorption spectra of benzene gas

XBL 872-6150

*LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720*