

**REPORT DOCUMENTATION PAGE**

Form Approved  
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Service Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

**PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.**

<b>1. REPORT DATE (DD-MM-YYYY)</b> 1 Jan 2007		<b>2. REPORT TYPE</b> Final Technical Report		<b>3. DATES COVERED (From - To)</b> 1 Jan 2007-28 Feb 2010	
<b>4. TITLE AND SUBTITLE</b> VIBRATIONAL AND ELECTRONIC DYNAMICS OF PHOTOEXCITED MOLECDULES IN SOLUTION				<b>5a. CONTRACT NUMBER</b>	
				<b>5b. GRANT NUMBER</b> FA9550-07-1-0062	
				<b>5c. PROGRAM ELEMENT NUMBER</b>	
				<b>5d. PROJECT NUMBER</b>	
				<b>5e. TASK NUMBER</b>	
<b>6. AUTHOR(S)</b> Fleming Crim				<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> Board of Regents Department of Chemistry 1101 University Ave Madison, WI 53706-1411				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Air Force Office of Scientific Research 875 North Randolph Street Arlington, VA 22203				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b>	
				<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b> AFRL- AFOSR-VA-TR-2016-0676	
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b> Distribution Statement A: Approve for public release. Distribution is unlimited					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> This research focused on three topics that are critical to understanding and exploiting vibrational excitation in photoisomerization dynamics. The first aspect is exploring energy flow within a vibrationally excited molecule and into the surrounding the solvent.					
<b>15. SUBJECT TERMS</b>					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON</b> Fleming Crim
<b>a. REPORT</b>	<b>b. ABSTRACT</b>	<b>c. THIS PAGE</b>			<b>19b. TELEPHONE NUMBER (Include area code)</b> 608-263-7364
	unclassified	unclassified			

---

**FINAL TECHNICAL REPORT**

**VIBRATIONAL AND ELECTRONIC DYNAMICS OF PHOTOEXCITED MOLECULES IN  
SOLUTION**

**FA9550-07-1-0062**

**Principal Investigator  
Fleming Crim**

**Department of Chemistry**

**1101 University Ave**

**Madison, WI 53706-1411**

This research focused on three topics that are critical to understanding and exploiting vibrational excitation in photoisomerization dynamics. The first aspect is exploring energy flow within a vibrationally excited molecule and into the surrounding the solvent. The second aspect is intercepting the vibrationally excited molecule at different times to promote it to an electronically excited state with energy in selected vibrational motions, and the third aspect is probing the molecule in its excited state.

### VIBRATIONAL ENERGY FLOW

Direct observation of intramolecular and intermolecular energy flow is an essential preparatory step for all of the studies performed in this research and is the most mature component of our experiments. The energy transfer experiments used ultrafast transient electronic absorption to probe vibrationally excited molecules as they redistributed energy internally and transferred it to the surrounding solvent. Figure 1 schematically illustrates the approach, which relies on changes in the Franck-Condon factor for the electronic transition as vibrational energy flows around the molecule. A 100-fs pulse of infrared light excited a fundamental or overtone vibration, such as the two quanta of C-H stretch of  $\text{CH}_2\text{I}_2$  shown in the figure, and a second ultraviolet pulse transferred the molecule to an excited state.

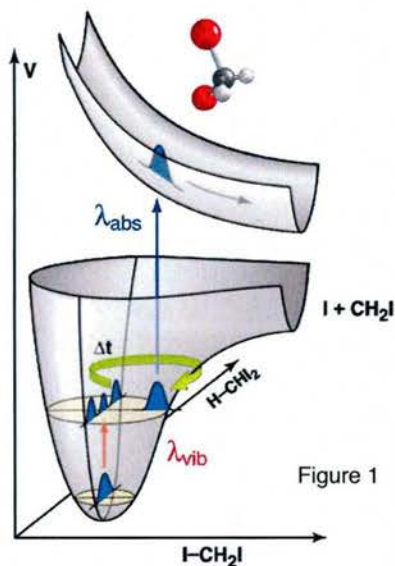


Figure 1

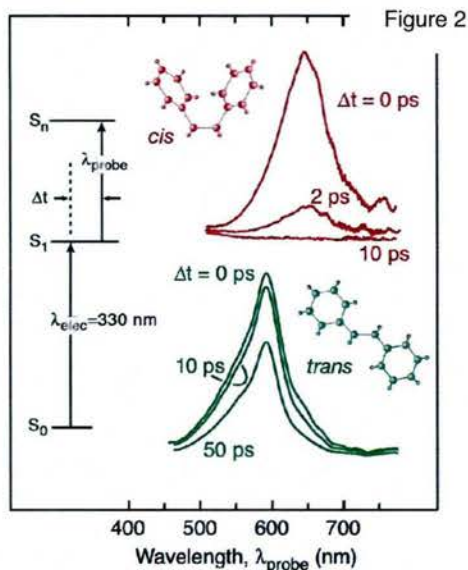
When the vibrational excitation was in the C-H stretch, there was little absorption because the Franck-Condon factor for reaching the excited state is poor. However, the absorption increased when energy flowed into modes with better Franck-Condon factors, such as the C-I stretch.

The rise and decay of this absorption mirrored the flow of vibrational energy around the molecule and into the solvent.<sup>1</sup> This approach has monitored energy flow in gas phase molecules<sup>2,3</sup> and, most important in the present context, in solution phase molecules.<sup>3-8</sup> For example, the measurements showed that intramolecular energy flow takes about 10 ps and intermolecular energy flow (into the solvent) takes about 70 ps in  $\text{CH}_2\text{I}_2$  molecules containing two quanta of C-H stretching excitation.<sup>4</sup> One of the most important observations was that some molecules have multiscale intramolecular energy redistribution in which vibrational energy initially flows into a subset of the available states and subsequently enters the remainder, perhaps on the same timescale as it flows into the solvent.<sup>3,8</sup> Another important observation was that initial vibrational relaxation in stilbene, one of the target molecules for photoisomerization studies, occurred within a few ps and was different for the *cis* and *trans* isomers.<sup>8</sup>

### EXCITED-STATE DYNAMICS

Intercepting the vibrationally excited molecule during its relaxation allowed both the observation of energy flow and the transfer the molecule to unique regions of an electronically excited surface. The approach to studying excited-state dynamics used in this research was broadband, transient electronic absorption. This approach provided the time-resolved excited-state absorption spectrum of the molecule as it evolved in the excited state. Figure 2 shows transient absorption spectra of *cis*- and *trans*-stilbene at different times after one-photon excitation with  $\lambda_{elec} = 330$  nm to the excited state ( $S_1$ ) in hexane solution. The broadband continuum pulse came from focusing a small amount of 800-nm light on a sapphire sub-

strate, and passing that light through the sample and dispersing it, along with a reference beam, onto a pair of photodiode arrays produced the excited-state spectrum ( $S_n \leftarrow S_1$ ) after excitation to  $S_1$ .



These spectra monitored the evolution of the excited-state population. For example, the *cis*-stilbene absorption decayed in about 2 ps as the molecule left the Franck-Condon region and returned to the ground state through a conical intersection. However, the *trans*-stilbene signal survived for almost 100 ps because there is a barrier to its leaving the excitation region and moving toward the conical intersection, behavior that is consistent with extensive previous studies of the one-photon excitation.<sup>9</sup> We also monitored the rotational diffusion in the excited state using excitation and probe light with both parallel and perpendicular relative polarizations.

Our goal was to explore the effect of vibrations on excited-state dynamics, and a major step toward that goal was a vibrationally mediated isomerization experiment on stilbene. In this measurement, we monitored the evolution of the population of the electronically excited state following promotion of a vibrationally excited molecule from its ground electronic state. We were barely able to observe such a signal using our original laser system, but its replacement with a modern ultrafast laser made those experiments work well and opened the door to an ambitious new set of measurements.

The experiment was essentially the same as the excited-state absorption measurement described above except that two-step excitation through a vibrationally excited intermediate state replaced the one-photon excitation. Figure 3 shows the excitation scheme and data that for *trans*-stilbene. A pulse of infrared light ( $\lambda_{vib}$ ) prepared the molecule with two quanta of C-H stretching excitation, and a second pulse of ultraviolet light ( $\lambda_{elec}$ ) that arrived at a variable time  $\Delta t_{S_0}$  after the vibrational excitation pulse promoted the molecule to the excited state. The broadband continuum probe pulse ( $\lambda_{probe}$ ) arrived at a time  $\Delta t_{S_1}$  after the electronic excitation pulse, and changing the two delays allowed observation of the evolution of the vibrationally excited molecule.

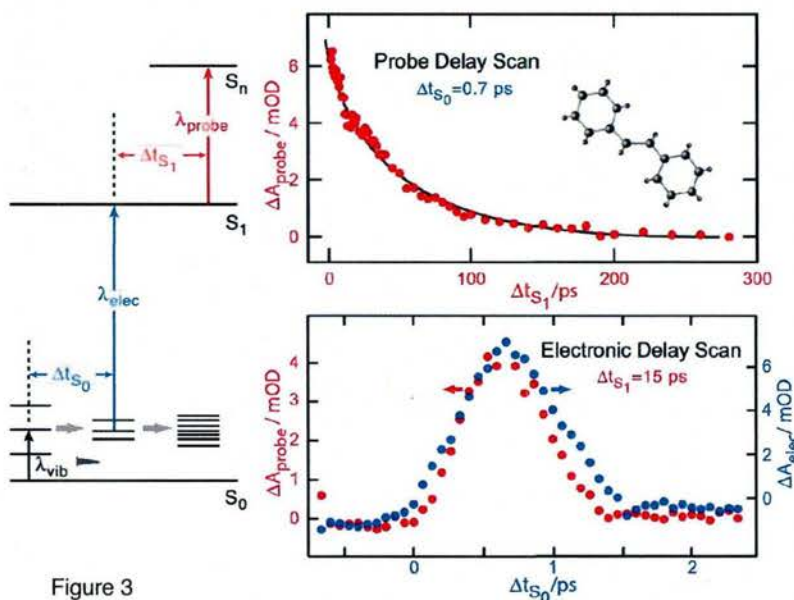


Figure 3

Varying the delay  $\Delta t_{S_0}$  tracked the evolution in the ground state, and varying  $\Delta t_{S_1}$  monitored the progress of the molecule in the excited state. (The horizontal arrows in the figure schematically indicate the flow of energy among the vibrational states.)

The upper panel in the figure is an example of the signal obtained by varying  $\Delta t_{S_1}$  with the ground-state delay fixed at  $\Delta t_{S_0} = 0.7$  ps. It shows the decay of the excited-state absorption following electronic excitation of a *trans*-stilbene molecule initially prepared with two quanta of C-H stretching excitation in a solution of deuterated chloroform ( $\text{CDCl}_3$ ). The decay time of about 40 ps was shorter than the 60 ps measured for single-photon excitation. Careful measurements, including the dependence on the relative polarization of the three pulses, permitted comparison of the excited-state behavior at the same total energy for different excitation schemes. These comparisons, which allowed probing of the influence that the vibrational excitation has on the dynamics in the excited state, would be impossible without the improved stability and pulse energy of our new laser system. The experiment captured the entire broadband absorption spectrum between 400 nm and 700 nm even though the figure only shows the evolution at the maximum of the excited-state absorption.

The lower panel shows the ground state evolution probed by simultaneously monitoring the electronic absorption ( $\Delta A_{elec}$ ) of the vibrationally excited molecule (blue points-right axis) and the excited-state absorption ( $\Delta A_{probe}$ ) of the electronically excited molecule (red points-left axis) at a time  $\Delta t_{S_1} = 15$  ps. The measurement of  $\Delta A_{elec}$  was the same as our previous vibrational energy transfer experiments in which we monitored the evolution of the transient electronic absorption of the vibrationally excited molecule. However, the measurement of  $\Delta A_{probe}$  added an additional dimension because it reflects both the probability of a transition to the excited state *and* the probability of absorption from that state to the higher electronic state. In favorable cases, this absorption carries information on the changes that arise from intercepting the vibrationally evolving ground electronic state molecule at different times.

1. C. G. Elles and F. F. Crim, *Connecting chemical dynamics in gases and liquids*, Annu. Rev. Phys. Chem. **57**, 273 (2006).
2. D. Bingemann, M. P. Gorman, A. M. King, and F. F. Crim, *Time-resolved vibrationally mediated photodissociation of  $\text{HNO}_3$ : Watching vibrational energy flow*, J. Chem. Phys. **107**, 661 (1997).
3. C. G. Elles, M. J. Cox, and F. F. Crim, *Vibrational relaxation of  $\text{CH}_3\text{I}$  in the gas phase and in solution*, J. Chem. Phys. **120**, 6973 (2004).
4. D. Bingemann, A. M. King, and F. F. Crim, *Transient electronic absorption of vibrationally excited  $\text{CH}_2\text{I}_2$ : Watching energy flow in solution*, J. Chem. Phys. **113**, 5018 (2000).
5. C. M. Cheatum, M. M. Heckscher, D. Bingemann, and F. F. Crim,  *$\text{CH}_2\text{I}_2$  fundamental vibrational relaxation in solution studied by transient electronic absorption spectroscopy*, J. Chem. Phys. **115**, 7086 (2001).
6. M. M. Heckscher, L. Sheps, D. Bingemann, and F. F. Crim, *Relaxation of the C-H stretching fundamental vibrations of  $\text{CHI}_3$ ,  $\text{CH}_2\text{I}_2$ , and  $\text{CH}_3\text{I}$  in solution*, J. Chem. Phys. **117**, 8917 (2002).
7. C. G. Elles, D. Bingemann, M. M. Heckscher, and F. F. Crim, *Vibrational relaxation of  $\text{CH}_2\text{I}_2$  in solution: Excitation level dependence*, J. Chem. Phys. **118**, 5587 (2003).
8. M. J. Cox and F. F. Crim, *Vibrational energy flow rates for cis- and trans-stilbene isomers in solution*, J. Phys. Chem. A **109**, 11673 (2005).
9. S. T. Repinec, R. J. Sension, A. Z. Szarka, and R. M. Hochstrasser, *Femtosecond laser studies of the cis-stilbene photoisomerization reactions - the cis-stilbene to dihydrophenanthrene reaction*, J. Phys. Chem. **95**, 10380 (1991).