

## Application of PET Deprotection for Orthogonal Photocontrol of Aqueous Solution Viscosity

J. Brian Borak,<sup>1</sup> Hee-Young Lee,<sup>2</sup> Srinivasa R. Raghavan,<sup>2</sup> and Daniel E. Falvey<sup>1\*</sup>  
<sup>1</sup>*Department of Chemistry and Biochemistry, and* <sup>2</sup>*Department of Chemical and Biomolecular Engineering,*  
*University of Maryland, College Park, MD 20742*

**falvey@umd.edu**

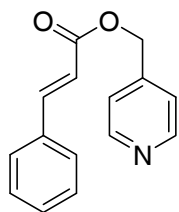
### SUPPORTING INFORMATION

Section	Starting Page
General Experimental Procedures	S2
Synthetic Procedures	S3
Viscosity Change Photolysis Procedures	S4
NMR Analyses of CTAB/tCA Mixtures	S6
Control Photolysis and Rheology	S6
Molecular Modeling	S13
Mechanistic Studies by Laser Flash Photolysis	S14

## **GENERAL EXPERIMENTAL PROCEDURES**

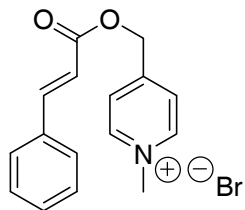
All  $^1\text{H}$  and  $^{13}\text{C}$  NMR were obtained on a Bruker 400 MHz spectrometer. Chemical shifts ( $\delta$ ) are reported in parts per million (ppm) and are referenced to TMS or as indicated. Coupling constants ( $J$ ) are reported in Hertz (Hz). Thin-layer chromatography (TLC) was performed on Merck silica-coated glass plates with UV254 indicator. Compounds were visualized under 254 nm UV irradiation or by treatment with  $\text{I}_2$ . All flash chromatography was carried out using Silicycle Silia-P Flash Silica Gel (60 Å pore diameter, 40-63  $\mu\text{m}$  particle size). UV-VIS spectra were obtained on a Perkin-Elmer Lambda 2S spectrophotometer. IR spectra were recorded on a Thermo Nicolet IR200 spectrometer. HPLC chromatograms were obtained on a dual Rainin HPXL pump system equipped with a  $\text{C}_{18}$  reversed-phase column and UV-VIS detector. Elution programs and solvent systems are described in the each respective section.

## SYNTHETIC PROCEDURES



### **Picolyl *trans*-cinnamate**

Picolyl *trans*-cinnamate was prepared according to previously reported procedures.<sup>1</sup> **<sup>1</sup>H NMR** (CDCl<sub>3</sub>) δ 5.27 (s, 2H), 6.53 (d, *J* = 16.0 Hz, 1H), 7.31 (d, *J* = 5.8 Hz, 2H), 7.40 (m, 3H), 7.55 (m, 2H), 7.78 (d, *J* = 16.0 Hz, 1H), 8.63 (d, *J* = 6.1 Hz, 2H); **<sup>13</sup>C NMR** (CD<sub>3</sub>CN) δ 65.1, 118.5, 122.8, 129.3, 130.0, 131.6, 135.3, 146.3, 146.7, 150.9, 167.2 <sup>1</sup>H and <sup>13</sup>C spectra are in agreement with previously reported spectra.



### ***N*-methylpicolinium *trans*-cinnamate bromide (NAP-tCA)**

A solution of picolyl *trans*-cinnamate (1.0 g, 4.18 mmol) in anhydrous, distilled acetonitrile (10 mL) was prepared in an oven-dried round bottom flask. The round-bottom flask was equipped with a dry ice condenser filled with isopropanol and dry ice. 2 M bromomethane in *tert*-butylmethyl ether (Aldrich, 6.3 mL, 12.54 mmol) is added to the flask by syringe and the solution is heated to reflux and stirred for 3 h. TLC (1/1 EtOAc/hexanes) after 3 h shows no visible sign of starting material. Ethyl acetate is added to precipitate the crude product. Subsequent recrystallization from ether/chloroform/ethanol (7/2/1) affords white needle-like crystals (1.19 g, 85 %). **Mp** 138-140 °C; **<sup>1</sup>H NMR** (CD<sub>3</sub>CN) δ 4.31 (s, 3H), 5.50 (s, 2H), 6.68 (d, *J* = 16.0 Hz, 1H), 7.46 (m, 3H), 7.69 (m, 2H), 7.84 (d, *J* = 16.1 Hz, 1H), 8.00 (d, *J* = 6.4 Hz, 2H), 8.68 (d, *J* = 6.7 Hz, 2H); **<sup>13</sup>C NMR** (CD<sub>3</sub>CN) δ 48.9, 64.3, 117.9, 126.1, 129.5, 130.1, 131.9, 135.2, 146.4, 147.1, 157.6, 166.9 <sup>1</sup>H and <sup>13</sup>C NMR data are in agreement with previously published spectra for the perchlorate and iodide salts.<sup>1</sup>

## **VISCOSITY CHANGE PHOTOLYSIS PROCEDURES**

*Materials.* NAP-tCA was prepared as described in the Synthesis section. Tris(2,2'-bipyridyl)ruthenium(II) chloride hexahydrate (Rubpy) was used as received from Strem Chemicals. Ascorbic acid (ASC), cetyltrimethylammonium bromide (CTAB), *trans*-cinnamic acid (tCA) were used as received from commercial sources.

*Methods.* Photolysis solutions were prepared containing 50 mM CTAB, 0-20 mM tCA/NaOH, 30-50 mM ASC, and 2-5 mM Rubpy in deionized water. tCA was prepared in these solutions through dilution of a stock solution of equimolar tCA and sodium hydroxide in deionized water. 500  $\mu$ L of the photolysis stock was set aside in the dark as a control. The remaining amount was added to a 1 cm quartz cuvette fitted with a rubber septum. The solution was irradiated with constant stirring for prescribed periods of time by a 300 W tungsten/halogen lamp the output of which is passed through a 360 nm cutoff filter and a Kopp 7093 IR-absorbing filter to ensure visible light irradiation only. UV photolysis of solutions was performed with constant stirring using the unfiltered output of a 350 W Xe arc lamp. Aliquots of the dark control, visible light irradiated, and UV light irradiated samples were removed at the appropriate time for HPLC analysis. Prior to injection, samples were diluted with MeOH/MeCN (1/1) to disrupt any self-assembly in the solutions. HPLC gradient elution using an acetonitrile/acetate buffer (100 mM, pH 4.0) mixture that adjusts from 25% acetonitrile to 70 % acetonitrile over 20 min at a flow rate of 0.5 mL/min was sufficient to resolve the starting material and *cis* and *trans* isomers of the free acid, monitored at 254 nm. Estimated error in integration, 5%.

NOTE: Control experiments revealed a competitive photochemical reaction between Rubpy, ASC, and tCA (see following section “Mechanistic Studies by Laser Flash Photolysis”). Thus, despite quantitative deprotection of NAP-tCA, post-photolysis concentrations of tCA will be less than the sum of the starting concentrations of tCA and NAP-tCA.

### Selected Data from Visible and UV Photolysis Experiments

Entry	[NAP-tCA] <sub>0</sub> (mM) <sup>a</sup>	[tCA] <sub>0</sub> (mM) <sup>a</sup>	[Rubpy] <sub>0</sub> (mM)	Photolysis Conditions	VIS NAP-tCA Consumption (%) <sup>a</sup>	VIS [tCA] (mM) <sup>a</sup>	UV [tCA] (mM) <sup>a</sup>
1	51.3	-	5	3 h VIS, 2 h UV	97.0	12.1	4.3
2*	30.7	14.2	5	2 h VIS, 2 h UV	96.7	22.0	7.9
3	31.7	14.0	2	2 h VIS, 2 h UV	97.3	18.8	5.7
4*	28.3	20.5	2	1 h VIS, 2 h UV	95.8	29.9	9.6
5	29.5	18.6	2	10 min VIS	67.8	28.0	-

\*Data represent the average of two identical experiments <sup>a</sup>Determined by HPLC, estimated error 5%

### Steady-shear Rheology of Photolysis Mixtures:

Rheological studies were performed on a TA Instruments AR2000 stress controlled rheometer using a 20 mm couette geometry, maintained at 20° C by a Peltier-based temperature controller.

## **NMR ANALYSES OF CTAB/tCA MIXTURES**

### ***Addition of tCA to CTAB***

50 mM solutions of CTAB were prepared in D<sub>2</sub>O with varying concentrations of equimolar tCA and sodium deuteroxide (NaOD). Resonances were referenced to the H<sub>2</sub>O residual peak at 4.79 ppm.

### ***UV Light Photolysis***

Solutions of 10 mM tCA, 10 mM sodium deuteroxide, and 10 mM CTAB prepared in D<sub>2</sub>O were photolysed by broad band UV and visible light (250-800 nm). Spectra were recorded after specific irradiation periods; resonances referenced to H<sub>2</sub>O residual peak at 4.79 ppm.

## **CONTROL EXPERIMENTS**

### **VISIBLE LIGHT PHOTOLYSIS**

Control photolyses were performed in the absence of CTAB. Photolysis of aqueous solutions of equimolar Rubpy and NAP-tCA with broad band visible light (360 – 800 nm) resulted in 10 % consumption of NAP-tCA and a negligible amount of free tCA (as determined by HPLC). No detectable amount of photodimerization products was observed by HPLC or NMR in any samples.

### **UV LIGHT PHOTOLYSIS**

Control solutions of tCA irradiated with unfiltered broad band UV light for 2 h on a Xe arc lamp were converted to the *cis* isomer reaching a final *trans/cis* ratio of approximated 1/2. Solutions

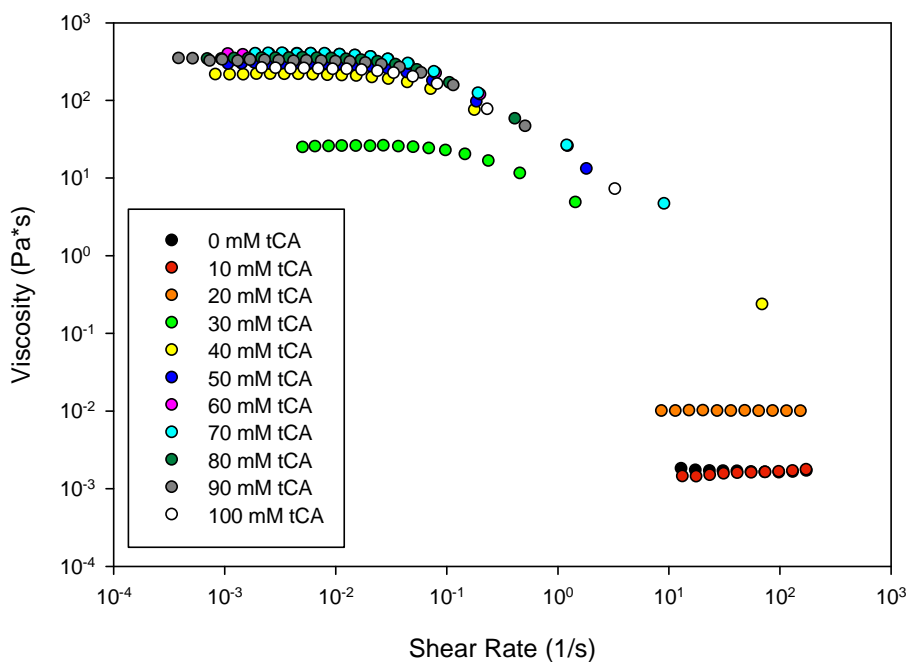
of NAP-tCA irradiated with UV light produced a mixture of products including the *cis* isomer of NAP-tCA and a negligible amount of free tCA. No detectable amount of photodimerization product was observed by HPLC or NMR in any samples.

## CONTROL RHEOLOGY

### *CTAB/tCA Standards*

Solutions prepared with 50 mM CTAB and varying concentrations of equimolar tCA/NaOH (as indicated) in H<sub>2</sub>O.

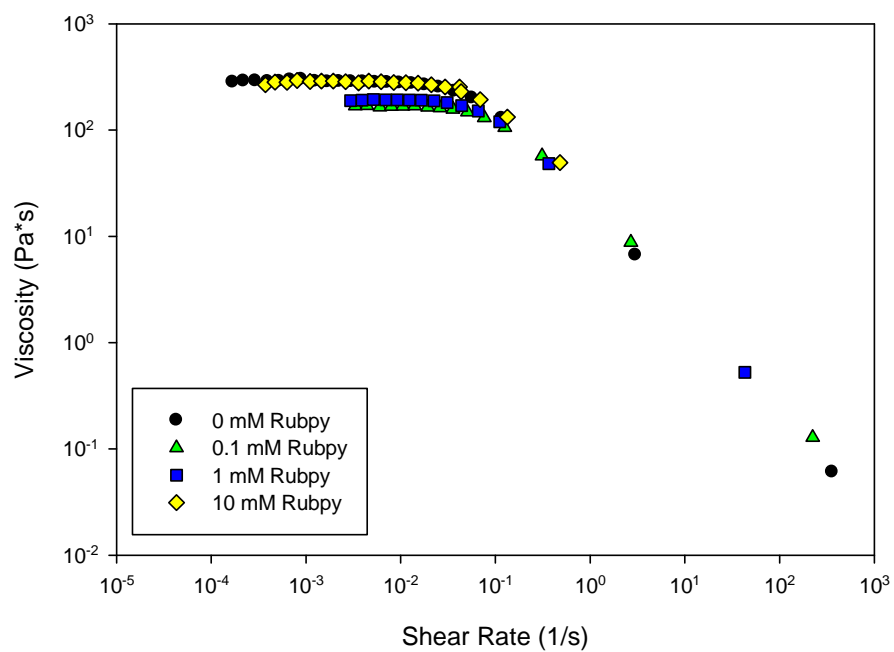
Figure S1.



### *Effect of Rubpy on Viscosity*

Solutions prepared with 50 mM CTAB, 50 mM tCA/NaOH in and varying concentrations of Rubpy (as indicated) in H<sub>2</sub>O.

**Figure S2.**

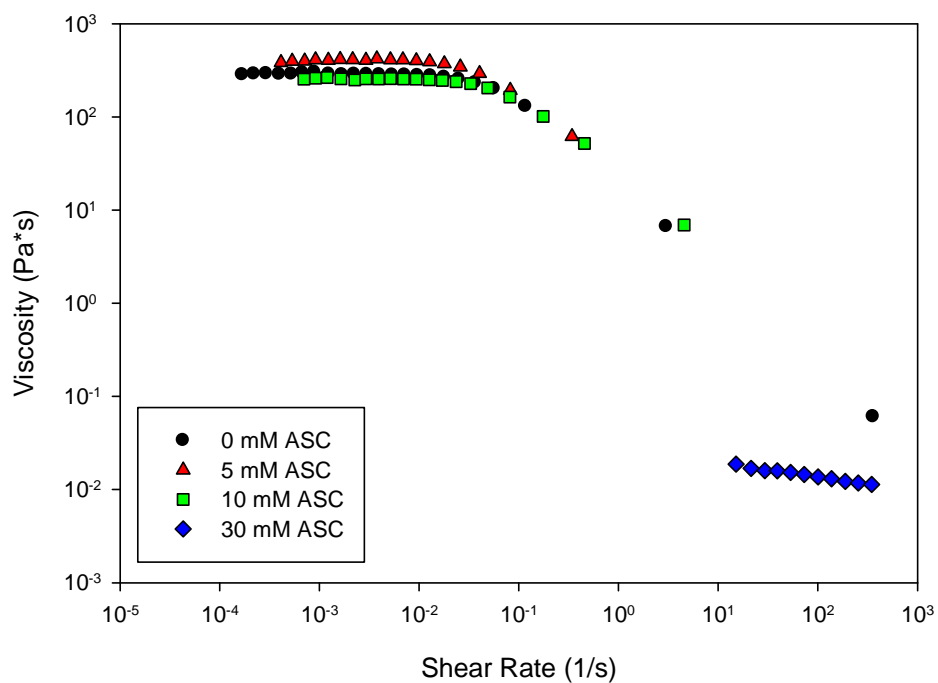




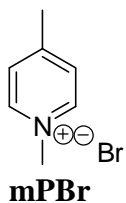
***Effect of Ascorbic Acid (ASC) on Viscosity***

Solutions prepared with 50 mM CTAB, 50 mM tCA/NaOH, and varying concentrations of ASC (as indicated) in H<sub>2</sub>O.

**Figure S3.**

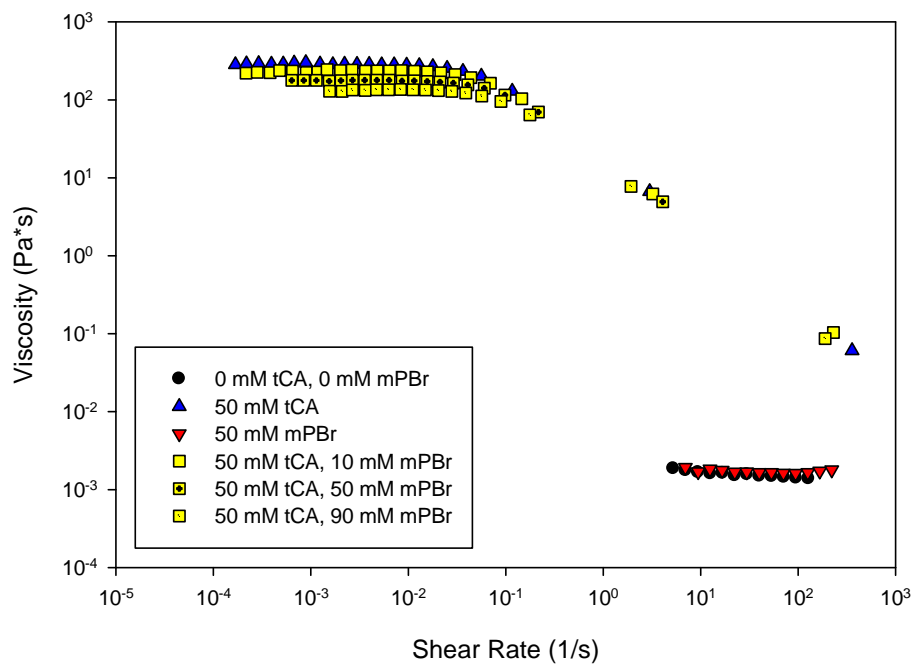


### Effect of NAP-photorelease Byproduct on Viscosity



Solutions prepared with 50 mM CTAB and varying concentrations of equimolar tCA/NaOH and 4-methylpyridinium bromide (mPBr) (as indicated) in H<sub>2</sub>O.

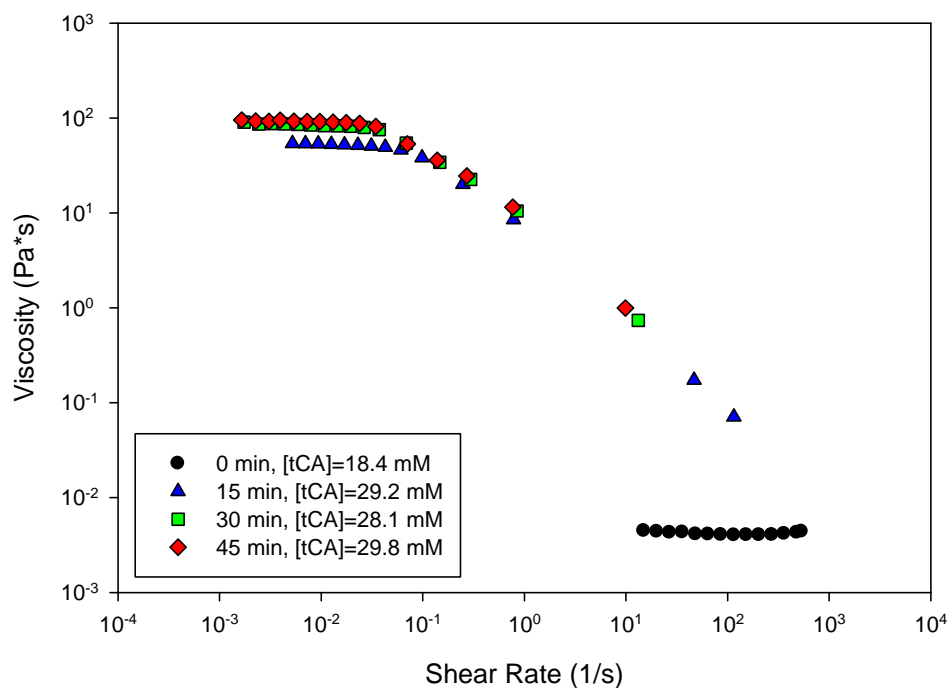
Figure S4.



### *Effect of VIS Irradiation Time on Viscosity*

Solutions were prepared with 50 mM CTAB, 30 mM NAP-tCA, 20 mM tCA/NaOH, and 30 mM ASC in H<sub>2</sub>O and photolyzed with broad band visible light (360-800 nm) with stirring for varying periods of time (as indicated). Concentrations listed for each time period are post-photolysis concentrations of tCA as determined by HPLC (see photolysis procedures).

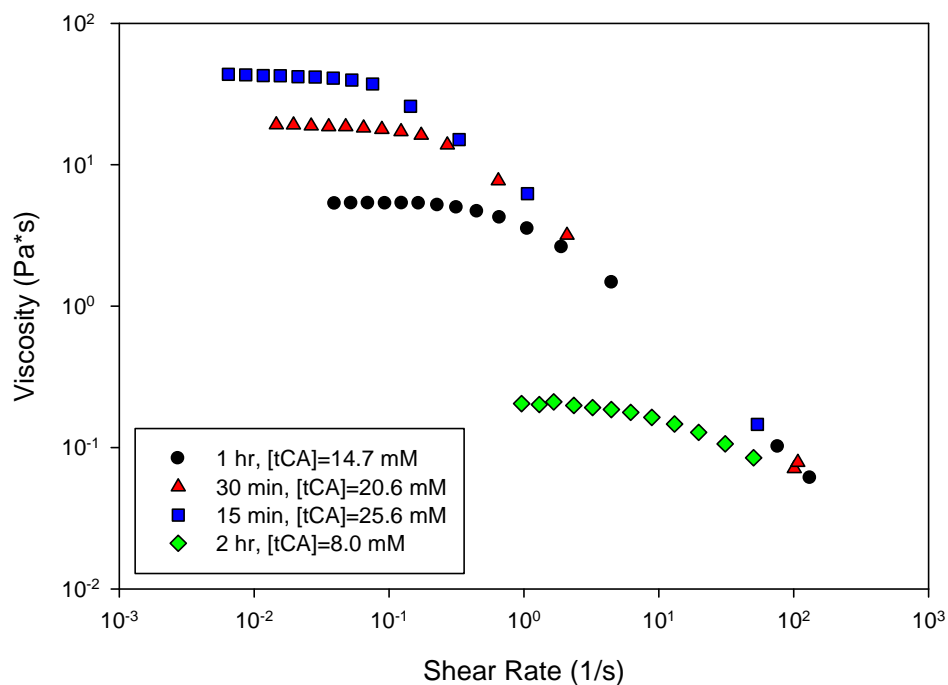
**Figure S5.**



### *Effect of UV Irradiation Time on Viscosity*

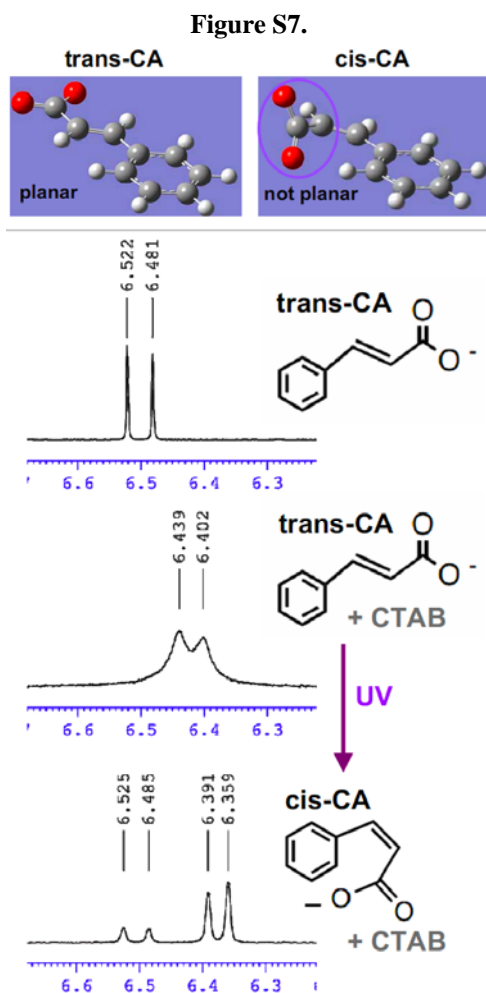
Solutions were prepared with 50 mM CTAB, 30 mM NAP-tCA, 20 mM tCA/NaOH, and 30 mM ASC in H<sub>2</sub>O and photolyzed with broad band visible light (360-800 nm) with stirring for 1 h. Each solution was subsequently irradiated with broad band UV light (250-800 nm) for various periods of time (as indicated). Concentrations listed for each time period are post-photolysis concentrations of tCA as determined by HPLC (see photolysis procedures).

Figure S6.



## MOLECULAR MODELING

Figure S7 shows minimum energy geometries, optimized at the B3LYP/6-31+G(d,p) level of density functional theory<sup>2</sup> for the *cis* and *trans* isomers of the cinnamate ion. That these stationary points correspond to local minima was confirmed by a vibrational energy calculation which showed no imaginary frequencies in either case. The *trans* form is predicted have a planar structure where the phenyl ring, the C=C double bond, and the carboxylate group all maintain a stabilizing conjugative interactions. On the other hand, the *cis* form is predicted to be non-planar as the carboxylate group rotates out of plane to avoid a steric clash with the phenyl C-H bonds that are *ortho* to the alkenyl group.

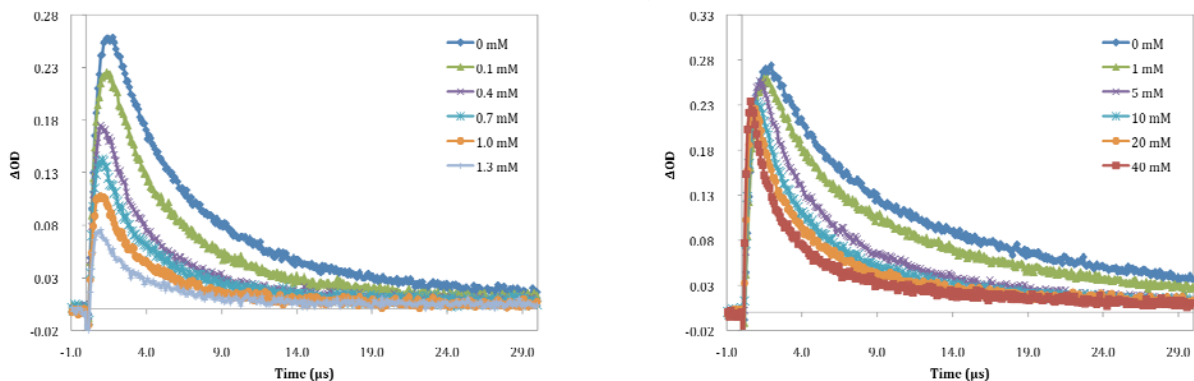


## **MECHANISTIC STUDIES BY LASER FLASH PHOTOLYSIS (LFP)**

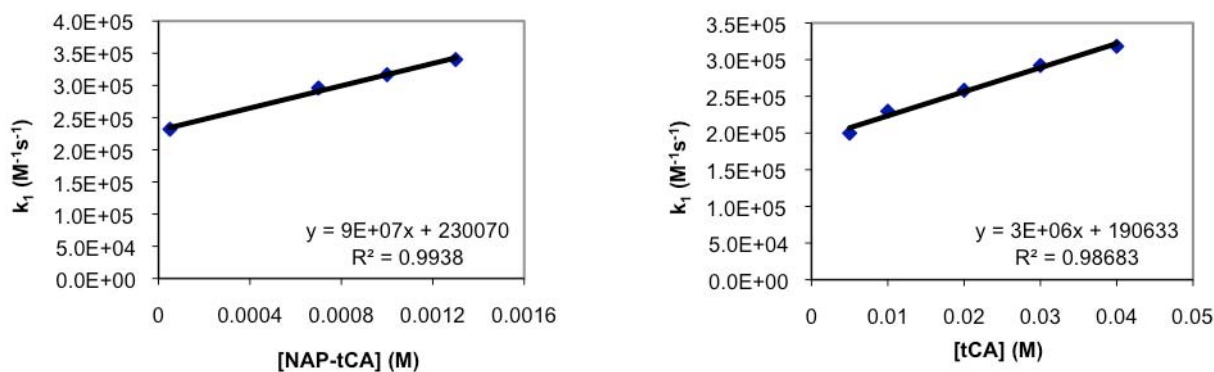
*Methods.* Samples were prepared in deionized water containing 10% MeOH and sufficient Rubpy was added such that the optical density at the excitation wavelength, 532 nm, was 0.5-0.6. The prepared samples were placed in a 1 cm quartz cuvette and sealed with a rubber septum. Samples were stirred continuously during photolysis. An Nd:YAG laser capable of 532, 355, and 266 nm pulses between 4-6 ns duration was used as the excitation source. A 350 W Xe arc lamp was used as the probe beam passed through a monochromator to a PMT detector. A 350 MHz digital oscilloscope was used to observe the traces which were subsequently recorded on a personal computer. Growth and decay curves were fit to model functions using the MathCAD software package.

*Discussion.* Experiments to ascertain the success of the desired electron transfer reactions and gather information about the side reaction were performed. Previous studies have shown the effective quenching of Rubpy\* by ASC to generate Rubpy<sup>+1</sup>.<sup>3,4</sup> Confirming control deprotection photolysis experiments that combined Rubpy with tCA, Rubpy luminescence was not quenched with added tCA. Thus, both the productive release of tCA from NAP-tCA and the side reaction appear to occur from Rubpy<sup>+1</sup> and we turned to LFP quenching studies.

LFP solutions were prepared with a fixed amount of Rubpy (0.8 mM) and a large excess of ASC (1 M) to ensure adequate production of Rubpy<sup>+1</sup>. Each solution contained 50 mM CTAB to ensure full solubility of ASC and tCA, however 10 % methanol was added to avoid the formation of micelles. Increasing amounts of Rubpy<sup>+1</sup> quencher (NAP-tCA or tCA) were added to these solutions and the growth and decay of Rubpy<sup>+1</sup> was monitored at 510 nm. Traces were fit to a model function containing exponential growth and decay terms with an added baseline correction term. (Equation 1)



**Figure S8: Transient absorption traces from 532 nm pulsed laser photolysis, monitored at 510 nm with varying concentrations of (LEFT) NAP-tCA or (RIGHT) tCA**



**Figure S9:  $k_1$  versus (LEFT) [NAP-tCA] or (RIGHT) [tCA] from quenching of LFP signals at 510 nm**

$$O.D. = A + OD_0 \left( \frac{k_1}{k_2 - k_1} \right) (e^{-k_1 t} - e^{-k_2 t}) \quad (1)$$

Both tCA and NAP-tCA quench the signal from Rubpy<sup>+1</sup> (Figure S8), indicating that electron transfer from Rubpy<sup>+1</sup> to either compound are possible mechanistic pathways. The rates of decay for each of the curves were plotted versus quencher concentration to determine the quenching rate constant of each process. (Figure S9) The electron transfer process from Rubpy<sup>+1</sup> to NAP-tCA ( $k_q = 9 \times 10^7 \text{ M}^{-1}\text{s}^{-1}$ ) is apparently an order of magnitude greater than electron transfer to tCA ( $k_q = 3 \times 10^6 \text{ M}^{-1}\text{s}^{-1}$ ). Thus, electron transfer to NAP-tCA is the dominant

process, however, an order of magnitude smaller difference in  $k_q$  for quenching of Rubpy<sup>+1</sup> by tCA indicates that this process is still fairly competitive when present in significant concentrations. It is likely that electron transfer to tCA is the dominant process leading to diminishment in tCA concentration during prolonged irradiation periods. However, the identity of the final products as a result of this process is unclear.

## REFERENCES

- (1) Sundararajan, C.; Falvey, D. E. *J. Org. Chem.* 2004, *69*, 5547-5554.
- (2) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; J. A. Montgomery, J.; T. Vreven, K. N. K.; Burant, J. C.; Millam, J. M.; Iyengar, S. S.; Tomasi, J.; Barone, V.; Mennucci, B.; Cossi, M.; Scalmani, G.; Rega, N.; Petersson, G. A.; Nakatsuji, H.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Klene, M.; Li, X.; Knox, J. E.; Hratchian, H. P.; Cross, J. B.; Bakken, V.; Adamo, C.; Jaramillo, J.; Gomperts, R.; Stratmann, R. E.; Yazyev, O.; Austin, A. J.; Cammi, R.; Pomelli, C.; Ochterski, J. W.; Ayala, P. Y.; Morokuma, K.; Voth, G. A.; Salvador, P.; Dannenberg, J. J.; Zakrzewski, V. G.; Dapprich, S.; Daniels, A. D.; Strain, M. C.; Farkas, O.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Ortiz, J. V.; Cui, Q.; Baboul, A. G.; Clifford, S.; Cioslowski, J.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Gonzalez, C.; Pople, J. A.; Revision C.02 ed.; Gaussian, Inc.: Wallingford, CT, 2004.
- (3) Kalyanasundaram, K. *Coord. Chem. Rev.* 1982, *46*, 159-244.
- (4) Borak, J. B.; Falvey, D. E. *J. Org. Chem.* 2009, *74*, 3894-3899.