Multi-state Photo-induced Relaxation and Photoisomerization Ability of Fumaramide Threads: a Computational and Experimental Study

Piero Altoè[a], Natalia Haraszkiewicz[b,†], Francesco G. Gatti[c,‡], Piet G. Wiering[b], Céline Frochot[b,ʃ], Albert M. Brouwer[b], Grzegorz Balkowski[b], Daniel Shaw[b], Sander Woutersen[b], Wybren Jan Buma[b], Francesco Zerbetto[a], Giorgio Orlandi[a], David A. Leigh[c], and Marco Garavelli[a,*]

[a]Dipartimento di Chimica "G.Ciamician", Università di Bologna, via Selmi 2, 40126 Bologna, Italy.

[b]Van't Hoff Institute for Molecular Sciences, University of Amsterdam, Nieuwe Achtergracht 166, 1018 WV Amsterdam, The Netherlands.

[c]School of Chemistry, University of Edinburgh, The King's Buildings, West Mains Road, Edinburgh, EH9 3JJ, U.K.

marco.garavelli@unibo.it

Supporting Information

S1 Conformational Analysis

[†] Present address: Biotechnology Department, Synthon BV Microweg 22, 6503 GN Nijmegen, The Netherlands

[‡] Present address: Dipartimento di Chimica, Materiali e Ingegneria Chimica "Giulio Natta", Politecnico di Milano, Via Mancinelli 7, 20131 Milano, Italy

[ʃ] Present address: DCPR, Nancy-University, CNRS, 1 rue Grandville BP 20451 F-54001, Nancy, France

The fumaric (trans) and maleic (cis) amides used in this work can adopt several low-energy conformations via rotations of the single bonds (C=C-C=O) and the amide bonds. In the rotaxanes the single-bond *cis* conformation for the *E*-threads, exemplified by the X-ray crystal structure of the rotaxane of *E*-**5**,[1] is the most favorable because it allows the formation of hydrogen bonds with the amide protons of the macrocycle. The fumaric amide unit is only slightly distorted from planarity. This type of conformation may be denoted as a c*E*c, where c indicates the cisoid nature of the single bond linking the C=C and C=O bonds. For the free fumaramides, c*E*t and t*E*t conformations may also be accessible. Density functional calculations for the model systems N,N'-dimethylfumaramide (*E*-**2**) and N,N',N'',N'''-tetramethylfumaramide (*E*-**3**) at the B3LYP/6-31G* level indicate, however, that such transoid conformations (t*E*t and c*E*t) are much less favorable.

For the maleamide *Z*-isomer of the *N*-methylated system, *Z*-**5** planar structures are not possible. In the c*Z*c conformer, which is predicted to be the most favorable for model system *Z*-**3**, the C=C-C=O dihedral angle is 57° degrees (B3LYP/6-31G*, see also Figure 14). Also in crystal structures of the corresponding rotaxane such twisted c*Z*c structures have been found.[1]

The dialkylmaleamides *Z*-**2** or *Z*-**4**, in contrast, can attain a planar structure by forming an internal hydrogen bond between the NH of one amide and the carbonyl group of the other (see also Figure 13). This leads to a relatively large chemical shift of the amide proton in ^{1}H NMR spectra (see below). This interpretation is confirmed by DFT calculations, see Figure S1.
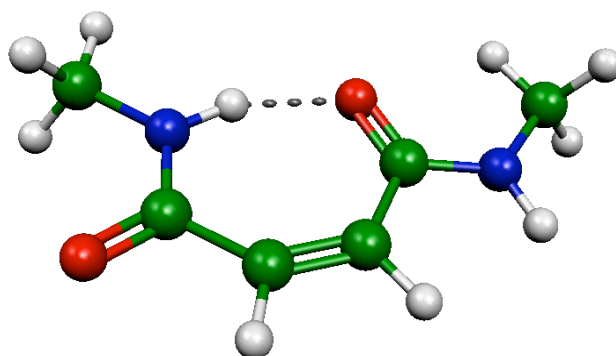

Figure S1. B3LYP/6-31G* computed structure of *Z*-**2** as a model for *Z*-**4**.

Another degree of freedom is in the rotation of the amide bonds. For the NH systems **2** and **4** the transoid conformation is strongly preferred, but for the *N*-methyl compounds the energy differences

---

[1] Gatti, F. G.; León, S.; Wong, J. K. Y.; Bottari, G.; Altieri, A.; Morales, A. M. F.; Teat, S. J.; Frochot, C.; Leigh, D. A.; Brouwer, A. M.; Zerbetto, F., Photoisomerization of a Rotaxane Hydrogen Bonding Template: Light-induced Acceleration of a Large Amplitude Rotational Motion. Proc. Natl. Acad. Sci. USA 2003, 100, (1), 10-14.

between the *cis* and *trans* amide conformers are small. This is clearly illustrated in the ^{1}H NMR spectrum of *E*-**4** (Figure S2), which reveals four peaks due to the *N*-methyl groups corresponding to two symmetric conformers (*cis, cis* and *trans, trans*) and one asymmetric conformer (*cis, trans = trans, cis*). The rotamers of the tertiary amides of the thread *E*-**4** are of roughly similar stabilities, and because of the partial double bond character of the C-N bond, interconvert only slowly at room temperature leading to the three rotamers visible in the ^{1}H NMR spectra. Signals from methyl protons at 2.72 and 2.89 ppm belong to asymmetric *cis, trans* and *trans, cis* amide rotamers. The signals at 2.78 and 2.82 ppm belong to the symmetric *cis, cis* and *trans, trans* conformers. The integral of the peak at 2.78 ppm is bigger than the one of the peak at 2.82 ppm, showing that the *cis, cis* symmetric form is probably more stable than the other (see Figure S2).

The fact that the symmetric and asymmetric amide rotamers are present is also evidenced by olefinic proton signals in ^{1}H NMR spectra. The AB pattern at 6.89 ppm and 7.05 ppm is due to the olefinic protons of asymmetric conformers. The singlet at 6.92 ppm originates from the minor symmetric conformer, probably *trans, trans*. Another singlet of the major symmetric conformer is hidden among the signals of the aromatic hydrogens.

Figure S2. ^{1}H NMR spectrum (CDCl₃, 400 MHz) of *E*-**4**.

Spectroscopic Implications. The presence of the different conformers is not likely to have a big effect on the observed photophysical properties. For **4**, only one conformer is significant, and this is the same in **2** and **1**. For *E*-**5** different conformers will have similar spectroscopic properties, because the electronic effects of methyl and 2,2-diphenylethyl groups are very similar. Small differences in the

excited state dynamics may explain why in some cases the decay kinetics appeared more complex than the simple biexponential decay found for *E*-**3**, but again, this does not affect the overall picture.

Photochemical Implications. The computational procedures used to trace the relaxations channels on the photochemically relevant excited states guarantee the location of the energetically most favored routes on the PESs. In fact, fully unconstrained optimizations have been adopted for the optimization of both critical and Minimum Energy Path points, while IRD computations assure to locate the most favored initial relaxation directions. That is, the molecular system is left free to relax on the PES without any geometrical constraint. As it is apparent from the discussion presented in the paper, excited state relaxation channels do not imply amide bond rotations, while central double bond rotation appears as the unique (although not very efficient) relaxation route (with reactant back formation being the most efficient process). In this context and with these premises, we can already safely state that rotations of amide bonds do not occur in the excited state (or, at least, these are much less favored then the documented paths). This conclusion may be also inferred by analyzing the molecular parameters for the relevant structures discussed in the paper (that are reported in Table 2). It is apparent that the photoinduced molecular relaxation (i.e. **FC→Min S_3→CI S_3/S_2→CI S_2/S_1 high→CI S_1/S_0 30°,** that preserves the planarity of the fumaramide moiety) involves a significant central (C1-C2) bond elongation (from 1.34 Å to 1.46 Å), while amide bonds (N2-C4 and N1-C3) remain substantially unchanged (ca. 1.36 Å, i.e. the preserves the strong double bond character seen in the ground state). This nicely accounts for central bond isomerization being triggered by light, while definitely calls for a very unfavored amide bond rotation in the excited state.

S2 Electronic absorption spectroscopy

Routine UV absorption spectra were recorded on an HP 8453 diode array spectrometer. To determine molar absorption coefficients and to measure the absorption of actinometers used for determination of the isomerization quantum yield a Cary 3E spectrophotometer (Varian) was used. The samples for the determination of the molar absorption coefficients were prepared in spectrograde solvents. The samples were contained in 1 cm rectangular quartz cuvettes.

S3 Irradiation experiments

Photostationary states. The isomerization at 300 nm or 254 nm was in most cases performed using a Rayonet photoreactor. The concentration of the samples was typically 1 mM, the volume of the solutions was 10 mL. The samples were purged with argon or N_2 for 15 min. before irradiation and during irradiation. Triplet sensitized isomerization was performed using the 350 nm lamps of the

Rayonet. The sensitizer concentration was 1-10 mM. Samples were periodically withdrawn and analyzed by means of ^{1}H NMR or HPLC.

In small-scale irradiation experiments 3 mL solutions of threads (1mM) in CH_3CN were irradiated with an Oriel 200 W high pressure Hg lamp in combination with a monochromator (Oriel 7240) set to 300 nm or with the 450 W Xe-arc lamp of a Spex Fluorolog 3 spectrofluorometer via the excitation monochromator set to 254 nm (bandwidth 5 nm). For triplet sensitization, a wavelength of 350 nm was used.

An overview of the results is given in Table S1 and in Figure 12 in the text.

HPLC analysis. The HPLC system consisted of: SCl-10A Shimadzu system controller, SPD-M10Avp-diode array detector (wavelength from 180 nm to 800 nm), LC-10AT-Shimadzu liquid chromatograph pump, FCV-10AL vp solvent mixer and DGU-14A degasser. The chromatographic data were stored and handled by a computer running the Shimadzu Class-VP ver.5.032 System software.

The separation was performed on a reverse phase column: SupelcosilTM LC18 (Supelco). A mobile phase, consisting of 50% acetonitrile and 50% of water or a gradient of these two solvents in time was used with a flow rate of 1 mL/min. 20 μL of the acetonitrile solutions of a concentration typically ca. 1×10^{-3} M were injected. Good separations of *E*-**5** and *Z*-**5**-threads were achieved with a fixed ratio of 50% water/50% acetonitrile. To separate *E*-**4**/*Z*-**4** isomers a time program was used, in which the fraction of acetonitrile was gradually increased to 100%. Calibration curves were generated by measuring HPLC peak areas for samples with a range of known concentrations.

Monitoring conversion by ^{1}H NMR. The solvent was removed from the samples taken from the reaction mixture under reduced pressure. The residue was dissolved in $CDCl_3$ and the spectrum measured (Bruker AM400). The *E*/*Z* ratio was calculated from the integrated peak intensities of characteristic signals of each isomer.

For *E*-**4** and *Z*-**4** the olefinic proton signals could be used, which are found at 6.65 and 5.90 ppm, respectively (singlets). Alternatively, the amide protons could be used (5.70 and 7.75 ppm, respectively). In the *N*-methyl compounds the situation is more complicated because three different amide conformations coexist which give their own sets of signals, as shown in Figure S2.[2] In this case

---

[2] at higher temperatures the signals coalesce, see ref. 1.

some of the olefinic proton signals coincide with aromatic proton resonances, but it proved possible to use the distinct singlets of the CH_3 groups for quantification.

Table S1. Conversion[a] of 4 and 5 in acetonitrile to the Z-isomers with different sensitizers.

sensitizer	triplet energy (kcal/mol)[b]		% Z-**4**	% Z-**5**
	nonpolar	polar		
1-acetonaphthone	56.4	56.4	0	0
chrysene		57.1	0	11
2-acetonaphthone	59.5	59.5	0	71
2,3-dicyano-1,4,8,9-tetraazatriphenylene		61.8[b]	0	100
phenanthrene	62.1	61.4	0	100
thioxanthone	63.3		0	100
triphenylene		66.9	35	100
2-methyl-1,4,8,9-tetraazatriphenylene		67.4[b]		100
fluorene	67.4	67.9	38	100
1,4,8,9-tetraazatriphenylene		68[b]	40.7[d]	100[d]
benzophenone	68.6	69.0	48 48.2[d]	100 97.4[d]
4,4'-dimethoxybenzophenone		70		100[d]
xanthone	74.1	74.1	47	70

[a] From ^{1}H NMR

[b] Except when noted otherwise: Murov, S. L.; Carmichael, I.; Hug, G. L. *Handbook of Photochemistry*; 2nd ed.; Marcel Dekker: New York, 1993.

[c] From phosphorescence in a 77 K glass of EtOH/MeOH: van der Tol, E. B.; van Ramesdonk, H. J.; Verhoeven, J. W.; Steemers, F. J.; Kerver, E. G.; Verboom, W.; Reinhoudt, D. N. Tetraazatriphenylenes as extremely efficient antenna chromophores for luminescent lanthanide ions. *Chemistry-A European Journal* **1998,** 4, (11), 2315-2323.

[d] From HPLC analysis

Photoisomerization quantum yields. The quantum yields were measured under conditions in which all photons impinging on the sample are absorbed, starting from a pure isomer, and with low conversion, so that the reverse reaction can be ignored. In such a case the quantum yield is simply derived from the rate of conversion. For example, starting from the pure *E* isomer:

$$\frac{d[Z]}{dt} = \frac{I_0 \phi_{E \to Z}}{V} \qquad \text{eq. S1}$$

In equation S1 *[Z]* is the concentration of the *Z* isomer (mol L^{-1}), I_0 is the absorbed photon flux in Einstein s^{-1}, $\phi_{E \to Z}$ the isomerization quantum yield for $E \to Z$ (mol Einstein^{-1}) and *V* the volume of the solution (L). Of course, an analogous equation describes d[*E*]/dt, when starting from *Z*-isomer, to give $\phi_{Z \to E}$. In the case of the direct irradiation, the light is absorbed by the substrates. In the case of sensitization, it is absorbed by the sensitizer (benzophenone), and the measured quantum yield is in fact a product of the quantum yields of inter system crossing, energy transfer, and isomerization. Since the former two are close to unity, we report the overall quantum yields as the triplet photoisomerization efficiencies. For the determination of the photon flux, we preferred actinometers with simple handling and evaluation.[3] At 254 nm we used the photocyclization of 1,3-cycloheptadiene (CHD) as actinometer,[4,5] At 350 nm, we used the Aberchrome photocyclization,[6] and the self-sensitized photooxygenation of 9,10-dimethylantracene.[7] An advantage of the latter is that the reagent is commercially available. Moreover, the reliability of Aberchrome 540 has been questioned.[8] In our hands, both methods yielded the same photon flux within 10%.

---

[3] Kuhn, H. J.; Braslavsky, S. E.; Schmidt, R., Chemical actinometry (IUPAC Technical Report). *Pure Appl. Chem.* **2004,** 76, (12), 2105–2146.

[4] Chapman, O.; Pasto, D.; Boerden, G.; Griswold, A. *J. Am. Chem. Soc.* **1962**, *84*, 1220-1225.

[5] Numao, N.; Hamada, T.; Yonemitsu, O. *Tetrahedron Lett.* **1977**, *19*, 1661-1664.

[6] Heller, H.G, Langan, J.R.; Davies, E. Photochromic heterocyclic fulgides .3. The use of (E)-alpha-(2,5-dimethyl-3-furylethylidene) (isopropylidene)succinic anhydride as a simple convenient chemical actinometer, *Journal of the Chemical Society-Perkin Transactions 2* **1981,** 341-343.

[7] Adick, H.-J.; Schmidt, R.; Brauer, H.-D., Two wavelength-independent chemical actinometers which together cover the range 334-500 nm. *J. Photochem. Photobiol. A-Chem.* **1988,** 45, 88-96.

[8] Yokoyama, Y.; Hayata, H.; Ito, H.; Kurita, Y., Photochromism Of A Furylfulgide, 2-[1-(2,5-Dimethyl-3-Furyl)Ethylidene]-3-Isopropylidenesuccinic Anhydride In Solvents And Polymer-Films. *Bulletin Of The Chemical Society Of Japan* **1990,** 63, (6), 1607-1610; Uhlmann, E.; Gauglitz, G., New aspects in the photokinetics of Aberchrome 540. *Journal Of Photochemistry And Photobiology A-Chemistry* **1996,** 98, (1-2), 45-49

In Table 3 in the paper the values of the isomerization quantum yields for both *E* and *Z*-isomers of the different compounds are reported. To calculate the isomerization quantum yields, the average of three independent measurements was taken.

S4 Complete references 26 and 29.

(26)   Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. A.; Jr., R. E. S.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Menucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Gonzalez, C.; Challacombe, M.; Gill, P. M. W.; Johnson, B. G.; Chen, W.; Wong, M. W.; Andres, J. L.; Gonzalez, C.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A.; Revision A.6 ed.; Gaussian Inc.: Pittsburgh PA, 1998.

(29)   Andersson, K.; Barysz, M.; Bernhardsson, A.; Blomberg, M. R. A.; Cooper, D. L.; Fülscher, M. P.; Graaf, C. d.; Hess, B. A.; Karlström, G.; Lindh, R.; Malmqvist, P.-Å.; Nakajima, T.; Neogrády, P.; Olsen, J.; Roos, B. O.; Schimmelpfennig, B.; Schütz, M.; Seijo, L.; Serrano-Andrés, L.; Siegbahn, P. E. M.; Stålring, J.; Thorsteinsson, T.; Veryazov, V.; Widmark, P.-O.; Version 5.4 ed.; Lund University, Sweden: 2002.

S5 Cartesian coordinates of all the structures discussed in the text.

Cartesian coordinate in Å, xyz format:

Optimized structures at CASSCF/6-31G*, active space 14 electrons in 10 orbitals:

FC

```
C   1.9449300   -0.4299090   -0.1256240
H   2.4598230   -1.3731700   -0.1194620
C   2.6516620    0.7083400   -0.1329850
H   2.1367690    1.6516020   -0.1388960
C   0.4526630   -0.4157850   -0.1259540
C   4.1439290    0.6942110   -0.1332910
O  -0.1878170    0.6070910   -0.1331200
```

O	4.7844080	-0.3286770	-0.1280100
N	-0.1333320	-1.6419850	-0.1173760
H	-1.1260100	-1.6984400	-0.1175080
H	0.3908430	-2.4842480	-0.1119400
N	4.7299250	1.9204240	-0.1397250
H	5.7226020	1.9768740	-0.1404700
H	4.2057500	2.7626930	-0.1442540

CI S$_1$/S$_0$ 30°

C	-0.2147150	0.5135150	0.8931760
C	-0.5646160	-0.8932690	1.0685470
H	0.1292340	0.8306020	1.8938980
H	-1.0654310	-1.2096960	1.9649230
C	-0.9572350	1.7803290	0.5521540
C	0.5992160	-1.5164070	0.6812190
O	-2.0939670	1.9342120	0.8978940
O	1.4007740	-0.6951040	-0.0342520
N	-0.1998250	2.7331020	-0.0297640
N	0.9684620	-2.8362940	0.8244350
H	-0.6025920	3.6253110	-0.2108450
H	1.7396470	-3.1098090	0.2525220
H	0.7032810	2.5314020	-0.3923890
H	0.2077390	-3.4819280	0.7696630

CI S$_1$/S$_0$ 90°

C	0.0481160	0.6157540	1.0009820
C	-0.3929720	-0.7872860	1.1020760
H	0.7896390	0.9996710	1.6837410
H	-1.1718870	-1.1613530	1.7310030
C	-0.6279680	1.5691120	0.0963780
C	0.3768450	-1.4847720	0.2414260
O	-1.7121230	1.3418850	-0.3881120
O	1.2462430	-0.7044820	-0.3825220
N	0.0286240	2.7618530	-0.1082040
N	0.4249370	-2.8432860	-0.0181350

H   -0.3512740   3.3148380   -0.8468720
H   0.7526780   -3.0617530   -0.9353060
H   1.0246440   2.7500800   -0.0782820
H   -0.4355030   -3.3102610   0.1784410

Min S₁

C   0.1083030   0.6877690   -0.1108510
C   -0.0421690   -0.7131210   -0.1493200
H   -0.7833340   1.2819700   -0.1125150
H   0.8109720   -1.3599850   -0.1563960
C   1.2969910   1.3440600   -0.0680860
C   -1.3833310   -1.3146960   -0.2059010
O   2.4861470   0.6683600   -0.0843830
O   -2.3955430   -0.6555750   -0.2595150
N   1.5029020   2.7055460   0.1243510
N   -1.4168250   -2.6906280   -0.2449480
H   2.1394500   3.1096050   -0.5334800
H   -2.3148460   -3.0920780   -0.0867530
H   0.6483390   3.2235340   0.1428120
H   -0.6566060   -3.1948190   0.1519140

Min T₁

C   0.0560460   0.7749870   -0.7342840
C   -0.2491650   -0.6556380   -0.8312590
H   -0.5606560   1.4903560   -1.2475860
H   0.2779770   -1.2691530   -1.5392550
C   1.1366100   1.2396000   0.1492420
C   -1.2346780   -1.2729060   0.0687820
O   1.8246190   0.4634010   0.7722830
O   -1.9605250   -0.6088360   0.7714580
N   1.3001650   2.5981400   0.2439970
N   -1.3249730   -2.6469130   0.0100280
H   2.1401250   2.9039610   0.6832730
H   -1.8614770   -3.0503420   0.7478310
H   0.9514030   3.1856510   -0.4782860

H -0.4950220 -3.1523650 -0.2092910

TS

C   0.0560460   0.7749870 -0.7342840

C -0.2491650 -0.6556380 -0.8312590

H -0.5606560   1.4903560 -1.2475860

H   0.2779770 -1.2691530 -1.5392550

C   1.1366100   1.2396000   0.1492420

C -1.2346780 -1.2729060   0.0687820

O   1.8246190   0.4634010   0.7722830

O -1.9605250 -0.6088360   0.7714580

N   1.3001650   2.5981400   0.2439970

N -1.3249730 -2.6469130   0.0100280

H   2.1401250   2.9039610   0.6832730

H -1.8614770 -3.0503420   0.7478310

H   0.9514030   3.1856510 -0.4782860

H -0.4950220 -3.1523650 -0.2092910

TS S$_0$

C   0.0522360   0.7793840 -0.7425220

C -0.2546770 -0.6539400 -0.8404680

H -0.5394460   1.4942140 -1.2852270

H   0.2377230 -1.2597030 -1.5795610

C   1.1153930   1.2411610   0.1608210

C -1.2206100 -1.2737480   0.0767490

O   1.7789020   0.4635600   0.8077690

O -1.9252990 -0.6125640   0.8026660

N   1.2905690   2.6017520   0.2509670

N -1.3209460 -2.6498210   0.0077810

H   2.1291330   2.8945180   0.7021910

H -1.8422790 -3.0503710   0.7582590

H   0.9887520   3.1783210 -0.5011040

H -0.4890020 -3.1528190 -0.2113890

CI S$_4$/S$_3$

```
C   -0.0298470    0.7664250   -0.0000040
C   -0.1307390   -0.6876260    0.0000040
H   -0.9078680    1.3753970   -0.0000050
H    0.7706550   -1.2693750    0.0000010
C    1.2250490    1.3153450   -0.0000010
C   -1.4271070   -1.3541640    0.0000090
O    2.3948800    0.6497630    0.0000030
O   -2.4747650   -0.7383700    0.0000010
N    1.4639200    2.6327940   -0.0000010
N   -1.4075810   -2.7222530    0.0000020
H    2.4145470    2.9412770    0.0000010
H   -2.2732850   -3.2094190   -0.0000040
H    0.7271100    3.3089920   -0.0000020
H   -0.5647890   -3.2446440   -0.0000030
```

CI S$_3$/S$_2$
```
C    0.1668250    0.6452650    0.0006490
C    0.0553960   -0.8111360    0.0018500
H   -0.7454860    1.1986860    0.0018710
H    0.9190050   -1.4409710    0.0009560
C    1.3316830    1.3338000   -0.0026800
C   -1.2811130   -1.3571870    0.0026890
O    2.5650010    0.7840590   -0.0044660
O   -2.2422090   -0.6071330   -0.0022760
N    1.3194940    2.6899640   -0.0001220
N   -1.5642160   -2.7001140    0.0002470
H    2.1901050    3.1897390   -0.0018860
H   -2.5198300   -2.9687960   -0.0024430
H    0.4517120    3.2032540    0.0041930
H   -0.8661880   -3.3952880    0.0014200
```

Min S$_3$
```
C    0.0323730    0.6976100   -0.0247620
C   -0.0642070   -0.7310090   -0.0238550
H   -0.8470020    1.2984380   -0.0261910
```

```
H    0.8152360   -1.3316960   -0.0269190
C    1.3083950    1.3002740    0.0387360
C   -1.3402710   -1.3338200    0.0373420
O    2.3949250    0.6386420    0.1091780
O   -2.4268130   -0.6726110    0.1082840
N    1.4059640    2.6479960    0.0558270
N   -1.4372900   -2.6813780    0.0525890
H    2.3137370    3.0570320   -0.0036300
H   -2.3445720   -3.0918130   -0.0030500
H    0.6143480    3.2173600   -0.1477270
H   -0.6446430   -3.2508800   -0.1458210
```

CI S$_2$/S$_1$

```
C   -0.0022060    0.7327600   -0.0042850
C   -0.1431970   -0.6870860   -0.0059590
H   -0.8606690    1.3732580   -0.0057310
H    0.7481450   -1.2839060   -0.0062640
C    1.2744060    1.3149190   -0.0003930
C   -1.3658540   -1.3618640   -0.0023250
O    2.3735270    0.6428540   -0.0032730
O   -2.4823670   -0.7277950   -0.0016540
N    1.4578320    2.6666470    0.0022840
N   -1.4247300   -2.7323180    0.0009370
H    2.3857650    3.0157520    0.0116540
H   -2.2967120   -3.2026610    0.0176060
H    0.7064190    3.3120610    0.0144860
H   -0.5936580   -3.2724600    0.0152830
```

High CI S$_2$/S$_1$

```
C    0.1399100    0.6218100   -0.0958900
C    0.0097200   -0.8322100   -0.0496000
H   -0.6659700    1.1615800   -0.5687700
H    0.8361300   -1.4619000   -0.3247600
C    1.3501600    1.3526500    0.0160600
C   -1.3038400   -1.3530100    0.0440000
```

```
O   2.5264900   0.8155800  -0.0259200
O  -2.2698000  -0.5405200   0.1953200
N   1.3296100   2.6963000   0.1288100
N  -1.5527200  -2.7051100   0.0213900
H   2.1996100   3.1862600   0.1797600
H  -2.4820300  -3.0241500   0.1732000
H   0.4744300   3.2081900   0.2041500
H  -0.8115400  -3.3613300   0.1022600
```

TS S$_0$
```
C   0.0522360   0.7793840  -0.7425220
C  -0.2546770  -0.6539400  -0.8404680
H  -0.5394460   1.4942140  -1.2852270
H   0.2377230  -1.2597030  -1.5795610
C   1.1153930   1.2411610   0.1608210
C  -1.2206100  -1.2737480   0.0767490
O   1.7789020   0.4635600   0.8077690
O  -1.9252990  -0.6125640   0.8026660
N   1.2905690   2.6017520   0.2509670
N  -1.3209460  -2.6498210   0.0077810
H   2.1291330   2.8945180   0.7021910
H  -1.8422790  -3.0503710   0.7582590
H   0.9887520   3.1783210  -0.5011040
H  -0.4890020  -3.1528190  -0.2113890
```

FC dimethyl-fumaramide
```
C  -0.3614022  -0.5633797   0.0181764
C   0.3614551   0.5634432  -0.0116221
H   0.1401321  -1.5124639   0.0678019
H  -0.1401215   1.5125433  -0.0603959
C  -1.8534679  -0.5296560  -0.0171978
C   1.8535896   0.5296877   0.0207527
O  -2.4777461   0.5019469  -0.0920989
O   2.4785343  -0.5031266   0.0670402
N  -2.4580831  -1.7427112   0.0281957
```

```
N    2.4578451    1.7436475   -0.0107440
H   -1.9009721   -2.5596670    0.1045674
H    1.9006335    2.5599474   -0.0936277
C   -3.8964606   -1.8720199    0.0097283
H   -4.1499362   -2.9219950    0.0614486
H   -4.3460947   -1.3615878    0.8524941
H   -4.3124821   -1.4565962   -0.8996280
C    3.8964236    1.8718348   -0.0207897
H    4.3279818    1.4077272   -0.8996015
H    4.1499574    2.9230900   -0.0202924
H    4.3306797    1.4078594    0.8554300
```

FC tetramethyl-fumaramide
```
C   -0.3559280   -0.4776120   -0.3085010
C    0.3547580    0.4786970    0.3060580
H    0.1325070   -1.1521780   -0.9848530
H   -0.1337000    1.1531440    0.9824870
C   -1.8341460   -0.5857140   -0.1096490
C    1.8330610    0.5862080    0.1076970
O   -2.4887680    0.3925970    0.1658130
O    2.4871230   -0.3922150   -0.1687830
N   -2.4141650   -1.8133700   -0.3299180
N    2.4139590    1.8130300    0.3306810
C   -3.8550990   -1.8821260   -0.1853050
H   -4.2111060   -2.7791160   -0.6773640
H   -4.1609230   -1.9139960    0.8584050
H   -4.3135860   -1.0225770   -0.6478340
C    3.8550110    1.8808620    0.1864930
H    4.1610370    1.9150200   -0.8570930
H    4.2117310    2.7763220    0.6808130
H    4.3126160    1.0197770    0.6470010
C   -1.7220560   -3.0492380   -0.0165470
H   -2.0679640   -3.8330360   -0.6797580
H   -0.6557970   -2.9504030   -0.1444380
H   -1.9101530   -3.3638540    1.0086110
```

C   1.7231300   3.0498330   0.0179420
H   0.6568780   2.9524340   0.1469030
H   2.0707170   3.8330500   0.6809370
H   1.9106980   3.3643220   -1.0073580