Trichocyanines: a Red-Hair-Inspired Modular Platform for Dye-Based One-Time-Pad Molecular Cryptography

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# SUPPORTING INFORMATION

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**Computational studies**

**Part 1.** Model compounds

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**Materials and methods**

Anhydrous ethyl ether, chloroacetone, phenacyl bromide, \( o \)-aminothiophenol, N,N-dimethylaminobenzaldehyde, N,N-dimethylaminocinnamaldehyde, vanillin and ferulaldehyde were purchased from Sigma-Aldrich.

UV spectra were recorded with a Jasco V-560 UV/VIS Spectrophotometer.

\(^1\)H and \(^{13}\)C NMR spectra were recorded in CDCl\(_3\) at 400 and 100 MHz, respectively. \(^1\)H,\(^1\)H COSY, \(^1\)H,\(^{13}\)C HSQC, and \(^1\)H,\(^{13}\)C HMBC were run at 400 MHz using Bruker standard pulse programs. Chemical shifts are reported in \( \delta \) values downfield from TMS.

LC-MS analyses were performed on an HPLC instrument Agilent 1100 Series MSD equipped with a UV-Vis detector and an electrospray ionization source in positive ion mode (ESI+). The spray voltage was set at 3.5 kV. Nitrogen was employed as both drying and nebulizer gas. Mass spectra were registered with the cone and the fragmentator voltage set at 4 kV and 80 V, respectively.
Fig. S1 NMR spectra of 3-methyl-2H-1,4-benzothiazine

$^1$H NMR, CDCl$_3$. 
$\textsuperscript{1}H, \textsuperscript{13}C$ HMBC NMR, CDCl$_3$. 
$^1$H, $^{13}$C HMBC NMR, CDCl$_3$, inset.
$^1$H, $^{13}$C HSQC NMR, CDCl$_3$. 
$^1$H, $^{13}$C HSQC NMR, CDCl$_3$, inset.
$^{13}$C, NMR, CDCl$_3$. 

![NMR Spectrum Image]
Fig. S2 NMR spectra of 1a

$^1$H NMR, CDCl$_3$. 
$^{1}H,^{1}H$ COSY NMR, CDCl$_3$. 
$^1$H, $^{13}$C HMBC NMR, CDCl$_3$. 
$^1$H, $^{13}$C HMBC NMR, CDCl$_3$, inset.
$^{1}\text{H}, ^{13}\text{C} \text{ HSQC NMR, CDCl}_3.$
$^{1}\text{H},^{13}\text{C}$ HSQC NMR, CDCl$_3$, inset.
$^{13}$C NMR, CDCl$_3$. 
$^{13}$C NMR, CDCl$_3$, inset.
Fig. S3 NMR spectra of 2a

$^1$H NMR, CDCl$_3$. 
$^1$H NMR, CDCl$_3$, inset.
$^{13}$C NMR, CDCl$_3$. 
$^{13}$C NMR, CDCl$_3$, inset.
$^1$H, $^{13}$C HSQC NMR, CDCl$_3$. 
$^1\text{H}, ^{13}\text{C}$ HSQC NMR, CDCl$_3$, inset.
$^{1}\text{H}, ^{13}\text{C} \text{HMBC NMR, CDCl}_3$. 
$^1$H, $^{13}$C HMBC NMR, CDCl$_3$, inset.
Fig. S4  NMR spectra of 3a

$^{1}H$ NMR, CDCl$_3$. 
$^1$H NMR, CDCl$_3$, inset.
$^{1}H,^{1}H$ COSY NMR, CDCl$_3$. 
$^1$H, $^{13}$C HMBC NMR, CDCl$_3$. 
$^1$H, $^{13}$C HMBC NMR, CDCl$_3$, inset.
$^{1}\text{H},^{13}\text{C}$ HSQC NMR, CDCl$_3$. 
$^{1}H,^{13}C$ HSQC NMR, CDCl$_3$, inset.
$^{13}$C NMR, CDCl$_3$. 

![NMR spectrum](image-url)
$^{13}$C NMR, CDCl$_3$, inset.
Fig. S5 NMR spectra of 4a

$^1$H NMR, CDCl$_3$. 
$^1$H NMR, CDCl$_3$, inset.
$^1$H, $^1$H COSY NMR, CDCl$_3$. 
$^1$H, $^{13}$C HMBC NMR, CDCl$_3$. 
$^1$H, $^{13}$C HMBC NMR, CDCl$_3$, inset.
$^{1}H, ^{13}C$ HSQC NMR, CDCl$_3$. 
$^1$H, $^{13}$C HSQC NMR, CDCl$_3$, inset.
$^{13}$C NMR, CDCl$_3$. 
$^{13}$C NMR, CDCl$_3$, inset.
Fig. S6 NMR spectra of 1b

$^1$H NMR, CDCl$_3$. 
$^1$H NMR, CDCl$_3$ inset.
$^{1}$H, $^{1}$H COSY NMR, CDCl$_3$. 
$^{13}$C NMR, CDCl$_3$. 
$^{13}$C NMR, CDCl$_3$, inset.
$^1$H, $^{13}$C HMBC NMR, CDCl$_3$. 
$^1$H, $^{13}$C HMBC NMR, CDCl$_3$, inset.
$^1$H, $^{13}$C HSQC NMR, CDCl$_3$. 
**Fig. S7** NMR spectra of 2b

$^1$H NMR, CDCl$_3$. 

![NMR spectrum](image-url)
$^1$H NMR, CDCl$_3$, inset.
$^1$H, $^{13}$C HSQC NMR, CDCl$_3$. 
$^1\text{H},^1\text{H COSY NMR, CDCl}_3$. 
$^{1}H,^{13}C$ HMBC NMR, CDCl$_3$. 
$^1$H, $^{13}$C HMBC NMR, CDCl$_3$, inset.
$^1$H, $^{13}$C HSQC NMR, CDCl$_3$. 
$^1$H, $^{13}$C HSQC NMR, CDCl$_3$, inset.
$^{13}$C NMR, CDCl$_3$. 
$^{13}$C NMR, CDCl$_3$, inset.
Fig. S8  NMR spectra of 3b

$^1$H NMR, CDCl$_3$. 
$^{1}H, ^{13}C$ HMBC NMR, CDCl$_3$. 
$^1$H, $^{13}$C HMBC NMR, CDCl$_3$ inset.
$^1H, ^{13}C$ HSQC NMR, CDCl$_3$. 
$^1$H, $^{13}$C HSQC NMR, CDCl$_3$, inset.
$^{13}$C NMR, CDCl$_3$. 
$^{13}$C NMR, CDCl$_3$, inset.
Fig. S9 NMR spectra of 4b

$^1$H NMR, CDCl$_3$. 

![NMR Spectra](image-url)
$^1$H NMR, CDCl$_3$, inset.
$^{13}$C NMR, CDCl$_3$. 

[Image of a NMR spectrum]
$^{13}$C NMR, CDCl$_3$, inset.
$^1$H, $^{13}$C HMBC NMR, CDCl$_3$. 
$^1\text{H}$, $^{13}\text{C}$ HSQC NMR, CDCl$_3$. 
$^{1}H,^{13}C$ HSQC NMR, CDCl$_3$, inset.
**Fig. S10** UV-Vis spectra of 1a

![UV-Vis spectra](image)

- MeOH
- Acid 1st shift
- Acid 2nd shift
Fig. S11  UV-Vis spectra of 2a
Fig. S12  UV-Vis spectra of 3a
Fig. S13  UV-Vis spectra of 4a
Fig. S14  UV-Vis spectra of 1b
Fig. S15  UV-Vis spectra of 2b
Fig. S16  UV-Vis spectra of 3b
Fig. S17 UV-Vis spectra of 4b
Table S1. UV vis absorption maxima and molar extinction coefficient at varying pHs for compounds 1-4

|       | 3-Ph     | 3-Me     |       |       |       |       |
|-------|----------|----------|-------|-------|-------|-------|
|       | 481 (3.71)| 605 (3.97)| 440 (3.96)| 1a     | 520 (4.03)| 686 (4.28)| 464 (4.26)| 2a     |
|       | 505 (3.36)| 644 (3.75)| 458 (3.65)| 2b     | 481 (3.50)| 581 (4.07)| 429 (3.85)| 1b     |
|       |          |          |        |       |       |       |       | 1b     |
|       |          |          |        |       |       |       |       | 2b     |
|       |          |          |        |       |       |       |       | 3b     |
|       |          |          |        |       |       |       |       | 4b     |
|       |          |          |        |       |       |       |       | 3a     |
|       |          |          |        |       |       |       |       | 4a     |
|       |          |          |        |       |       |       |       | HCl    |
|       |          |          |        |       |       |       |       | AcOH   |
|       |          |          |        |       |       |       |       | ----    |
|       |          |          |        |       |       |       |       | NH<sub>3</sub> |

**N-series↑**

| Charge | +2 | +1 | 0 | 0 |
|--------|----|----|---|---|

**O-series↓**

| Charge | +1 | +1 | 0 | -1 |
|--------|----|----|---|----|
Table S2. Calculated pKₐ for cyanines 1-4

| Compound | pKₐ₁ | pKₐ₂ |
|----------|------|------|
| 1a       | 3.5  |      |
| 2a       | 3.8  |      |
| 3a       | 2.8  | 10.1 |
| 4a       | 3.5  | 9.8  |
| 1b       | 4.2  |      |
| 2b       | 3.4  |      |
| 3b       | 4.8  | 9.7  |
| 4b       | 3.7  | 10.3 |
Fig.S18 Fluorescence spectra of 1a

- MeOH
- DCM
- MeOH 1st acidic shift
- MeOH 2nd acidic shift
Fig.S19 Fluorescence spectra of 2a
Fig.S20 Fluorescence spectra of 3a

- MeOH
- DCM
- MeOH acidic shift
- MeOH basic shift
Fig.S21 Fluorescence spectra of 4a

- MeOH
- DCM
- MeOH acidic shift
- MeOH basic shift
Fig.S22 Fluorescence spectra of 1b

MeOH

MeOH 1st acidic shift

MeOH 2nd acidic shift
Fig.S23 Fluorescence spectra of 2b
Fig. S24 Fluorescence spectra of 3b
**Fig. S25** Fluorescence spectra of 4b

- **MeOH**: Two peaks at 390 nm and 430 nm with excitation at 0 nm.
- **DCM**: A single peak at 0 nm with excitation at 430 nm.
- **MeOH acidic shift**: 0.26 peak at 600 nm.
- **MeOH basic shift**: 0.05 peak at 550 nm.
## Table S3: Emission wavelengths and quantum yields of cyanines 1-4 relative to rhodamine b

| Compound | $\lambda_{\text{max}}$ excitation (nm) | $\lambda_{\text{max}}$ emission (nm) | Quantum yield DCM | Quantum yield MeOH |
|----------|--------------------------------------|-------------------------------------|-------------------|--------------------|
| 1a       | 440                                  | 547                                 | 0.001             | 0.00022            |
| 2a       | 464                                  | 631                                 | 0.00089           | 0.00023            |
| 3a       | 413                                  | 527                                 | 0.00049           | 0.00012            |
| 4a       | 430                                  | 560                                 | 0.00033           | 0.00034            |
| 1b       | 429                                  | 545                                 | 0.0021            | 0.0038             |
| 2b       | 458                                  | 611                                 | 0.0013            | 0.0023             |
| 3b       | 401                                  | 502                                 | **0.011**         | **0.0018**         |
| 4b       | 400                                  | 525                                 | 0.004             | 0.00099            |
Computational studies

Part 1. Model compounds

Table 1.1. 4-(Dimethylamino)benzaldehyde: conformational exploration

Table 1.2. Vanillin: conformational exploration

Part 2. Cyanines derived from condensation of 1,4-benzothiazines with 4-(dimethylamino)benzaldehyde

Table 2.1. Parent benzothiazine: conformational exploration

Figure 2.1. Parent benzothiazine: TD-PBE0 calculations

Figure 2.2. Parent benzothiazine: TD-M06-2X calculations

Table 2.2. 3-Methylbenzothiazine: conformational exploration

Table 2.3. 3-Methylbenzothiazine: electronic transitions [TD-PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)] for the most stable structures identified, and isodensity maps (0.04 a.u.) of selected molecular orbitals

Figure 2.3. 3-Methylbenzothiazine: plot of selected orbital energies [PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)]

Figure 2.4. 3-Methylbenzothiazine: TD-PBE0 calculations

Figure 2.5. 3-Methylbenzothiazine: TD-M06-2X calculations

Table 2.4. 3-Phenylbenzothiazine: conformational exploration

Table 2.5. 3-Phenylbenzothiazine: electronic transitions [TD-PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)] for the most stable structures identified, and isodensity maps (0.04 a.u.) of selected molecular orbitals
Part 3. Cyanines derived from condensation of 1,4-benzothiazines with 4-(dimethylamino)cinnamaldehyde

Table 3.1. 3-Methylbenzothiazine: conformational exploration

Table 3.2. 3-Methylbenzothiazine: electronic transitions [TD-PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)] for the most stable structures identified, and isodensity maps (0.04 a.u.) of selected molecular orbitals

Figure 3.1. 3-Methylbenzothiazine: plot of selected orbital energies [PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)]

Figure 3.2. 3-Methylbenzothiazine: TD-PBE0 calculations

Figure 3.3. 3-Methylbenzothiazine: TD-M06-2X calculations

Table 3.3. 3-Phenylbenzothiazine: conformational exploration

Table 3.4. 3-Phenylbenzothiazine: electronic transitions [TD-PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)] for the most stable structures identified, and isodensity maps (0.04 a.u.) of selected molecular orbitals

Figure 3.4. 3-Phenylbenzothiazine: plot of selected orbital energies [PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)]

Figure 3.5. 3-Phenylbenzothiazine: TD-PBE0 calculations

Figure 3.6. 3-Phenylbenzothiazine: TD-M06-2X calculations

Part 4. Cyanines derived from condensation of 1,4-benzothiazines with vanillin
Table 4.1. 3-Methylbenzothiazine: conformational exploration

Table 4.2. 3-Methylbenzothiazine: electronic transitions [TD-PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)] for the most stable structures identified, and isodensity maps (0.04 a.u.) of selected molecular orbitals

Figure 4.1. 3-Methylbenzothiazine: plot of selected orbital energies [PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)]

Figure 4.2. 3-Methylbenzothiazine: TD-PBE0 calculations

Figure 4.3. 3-Methylbenzothiazine: TD-M06-2X calculations

Part 5. Comparisons

Figure 5.1. Plot of frontier orbital energies [PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)] of different cyanines as a function of protonation state

M. J. Frisch, et al. G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G. A. Petersson, H. Nakatsuji, M. Caricato, X. Li, H. P. Hratchian, A. F. Izmaylov, J. Bloino, G. Zheng, J. L. Sonnenberg, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, J. A. Montgomery Jr., J. E. Peralta, F. Ogliaro, M. Bearpark, J. J. Heyd, E. Brothers, K. N. Kudin, V. N. Staroverov, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, N. Rega, J. M. Millam, M. Klene, J. E. Knox, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, R. L. Martin, K. Morokuma, V. G. Zakrzewski, G. A. Voth, P. Salvador, J. J. Dannenberg, S. Dapprich, A. D. Daniels, Ö. Farkas, J. B. Foresman, J. V. Ortiz, J. Cioslowski, D. J. Fox, Gaussian 09, Revision A.01, Gaussian, Inc., Wallingford, CT, 2009.
Computational studies

Experimental

All calculations were performed with the Gaussian package of programs [Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Scalmani, G.; Barone, V.; Mennucci, B.; Petersson, G. A.; Nakatsuji, H.; Caricato, M.; Li, X.; Hratchian, H. P.; Izmaylov, A. F.; Bloino, J.; Zheng, G.; Sonnenberg, J. L.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Vreven, T.; Montgomery, J. A., Jr.; Peralta, J. E.; Ogliaro, F.; Bearpark, M.; Heyd, J. J.; Brothers, E.; Kudin, K. N.; Staroverov, V. N.; Kobayashi, R.; Normand, J.; Raghavachari, K.; Rendell, A.; Burant, J. C.; Iyengar, S. S.; Tomasi, J.; Cossi, M.; Rega, N.; Millam, N. J.; Klene, M.; Knox, J. E.; 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.; Martin, R. L.; Morokuma, K.; Zakrzewski, V. G.; Voth, G. A.; Salvador, P.; Dannenberg, J. J.; Dapprich, S.; Daniels, A. D.; Farkas, Ö.; Foresman, J. B.; Ortiz, J. V.; Cioslowski, J.; Fox, D. J. *Gaussian 09, Revision B.01*; Gaussian, Inc., Wallingford CT, 2009].

All structures were geometry optimized at the DFT level, with a hybrid functional (PBE0) [Adamo, C.; Barone, V. *J. Chem. Phys.* **1999**, *110*, 6158-6169] and a reasonably large basis set [6-31+G(d,p)]. For each species, different tautomers / conformers, as well as different protonation states were explored. In those cases where conformational enantiomers exist, a single enantiomeric series has been explored.

Computations were performed either in vacuo, or by adoption of a polarizable continuum medium (PCM) [(a) Miertus, S.; Scrocco, E.; Tomasi, J. *J. Chem. Phys.* **1981**, *55*, 117-129; (b) Cossi, M.; Scalmani, G.; Rega, N.; Barone, V. *J. Chem. Phys.* **2002**, *117*, 43-54; (c) Scalmani, G.; Barone, V.; Kudin, K. N.; Pomelli, C. S.; Scuseria, G. E.; Frisch, M. J. *Theor. Chem. Acc.* **2004**, *111*, 90-100; (d) Tomasi, J.; Mennucci, B.; Cammi, R. *Chem. Rev.* **2005**, *105*, 2999-3093] to account for the influence of the solution environment. In view of the faster convergence, a scaled van der Waals cavity based on universal force field (UFF) radii [Rappé, A. K.; Casewit, C. J.; Colwell, K. S.; Goddard, W. A. III; Skiff, W. M. *J. Am. Chem. Soc.* **1992**, *114*, 10024-10035] was used, and polarization charges were modeled by spherical Gaussian functions [(a) York, D. A.; Karplus, M. *J. Phys. Chem. A* **1999**, *103*, 11060-11079; (b) Scalmani, G.; Frisch, M. J. *Chem. Phys.* **2010**, *132*, 114110]. Vibrational-rotational contributions to the free energy were also computed.

UV-Vis spectra of the main species were computed in vacuo or in solution using the time-dependent density functional theory (TD-DFT) approach [((a) Stratmann, R. E.; Scuseria, G. E.; Frisch, M. J. *J. Chem. Phys.* **1998**, *109*, 8218-8224; (b) Bauernschmitt, R.; Ahlrichs, R. *Chem. Phys. Lett.* **1996**, *256*, 454-464; (c) Casida, M. E.; Jamorski, C.; Casida, K. C.; Salahub, D. R. *J. Chem. Phys.* **1998**, *108*, 4439-4449; (d) Adamo, C.; Scuseria, G. E.; Barone, V. *J. Chem. Phys.* **1999**, *111*, 2889-2899; (e) Scalmani, G.; Frisch, M. J.; Mennucci, B.; Tomasi, J.; Cammi, R.; Barone, V. *J. Chem. Phys.* **2006**, *124*, 094107], with the PBE0 functional and the 6-311++G(2d,2p) basis set. For comparison, TD-DFT calculations also were carried out with the M06-2X functional [Zhao, Y.; Truhlar, D. G. *Theor. Chem. Acc.* **2008**, *120*, 215-241], a hybrid meta-GGA which has proved satisfactory in reproducing the results of reference high-level post Hartree-Fock calculations of a series of...
cyanines [Jacquemin, D.; Zhao, Y.; Valero, R.; Adamo, C.; Ciofini, I.; Truhlar, D. G. *Chem. Theory Comput.* **2012**, *8*, 1255-1259], and moreover is available in the commercial Gaussian 09 package. To produce graphs, transitions below 5.6 eV were selected, and an arbitrary Gaussian line width of 0.15 eV was imposed; the spectra were finally converted to a wavelength scale.
## Part 1. Model compounds

### Table 1.1. 4-(Dimethylamino)benzaldehyde: conformational exploration

| Conformer | Schematic drawing | Symmetry | Selected dihedrals / deg | $E$ or $G_{PCM}$ / hartree (ΔE or Δ$G_{PCM}$ / kcal mol$^{-1}$) | $G_{RRHO}$ or $G_{PCM,RRHO}$ / hartree (Δ$G_{RRHO}$ or Δ$G_{PCM,RRHO}$ / kcal mol$^{-1}$) |
|-----------|------------------|----------|--------------------------|--------------------------------------------------|--------------------------------------------------|
| Neutral form in vacuo |
| cs.1 | ![Schematic drawing](image1) | $C_s$ | C2-C1-C(H)=O = 0.0 <br> C3-C4-N-C(H$_3$) = 0.0 <br> C3-C4-N-C(H$_3$) = 180.0 | -479.013887 (0.0) | -478.866813 (0.0) |
| Neutral form in methanol |
| cs.1 | ![Schematic drawing](image2) | $C_s$ | C2-C1-C(H)=O = 0.0 <br> C3-C4-N-C(H$_3$) = 0.0 <br> C3-C4-N-C(H$_3$) = 180.0 | -479.025382 (0.0) | -478.877717 (0.0) |
| Protonated form in methanol |

S100
| cs.1  | ![Structure](image) | Cs | \(-479.455567 (0.1)\) | saddle point |
|------|-----------------|----|--------------------------|-------------|
|      |                 | C2-C1-C(H)=O = 0.0 |             |             |
|      |                 | C3-C4-N(C(H3)) = 63.6 |             |             |
|      |                 | C3-C4-N(C(H3)) = -63.6 |             |             |
| cs.2 | ![Structure](image) | Cs | \(-479.455602 (0.1)\) | -479.292555 (0.0) |
|      |                 | C2-C1-C(H)=O = 0.0 |             |             |
|      |                 | C3-C4-N(C(H3)) = 116.2 |             |             |
|      |                 | C3-C4-N(C(H3)) = -116.2 |             |             |
| c1.1 | ![Structure](image) | approx. Cs | \(-479.455701 (0.0)\) | -479.292488 (0.0) |
|      |                 | C2-C1-C(H)=O = 0.0 |             |             |
|      |                 | C3-C4-N(C(H3)) = 63.7 |             |             |
|      |                 | C3-C4-N(C(H3)) = -63.7 |             |             |
| c1.2 | ![Structure](image) | Cs | \(-479.455558 (0.1)\) | -479.292222 (0.2) |
|      |                 | C2-C1-C(H)=O = 0.4 |             |             |
|      |                 | C3-C4-N(C(H3)) = 119.4 |             |             |
|      |                 | C3-C4-N(C(H3)) = -113.0 |             |             |
Table 1.2. Vanillin: conformational exploration

| Conformer | Schematic drawing | Symmetry  | $E$ or $G_{PCM}$ / hartree | $G_{RRHO}$ or $G_{PCM, RRHO}$ / hartree |
|-----------|------------------|-----------|-----------------------------|------------------------------------------|
|           |                  | $\Delta E$ or $\Delta G_{PCM}$ / kcal mol$^{-1}$ | $\Delta G_{RRHO}$ or $\Delta G_{PCM, RRHO}$ / kcal mol$^{-1}$ |
| Neutral form in vacuo |
| cs.1      | ![Schematic drawing](image1) | $C_s$ | -534.753238 (0.0) | -534.640247 (0.0) |
|           |                  | C2-C1-C(H)=O = 0.0 | | |
|           |                  | C2-C3-O-C(H$_3$) = 0.0 | | |
|           |                  | C3-C4-O-H = 0.0 | | |
| Neutral form in methanol |
| cs.2      | ![Schematic drawing](image2) | $C_s$ | -534.751232 (1.3) | -534.638482 (1.1) |
|           |                  | C2-C1-C(H)=O = 180.0 | | |
|           |                  | C2-C3-O-C(H$_3$) = 0.0 | | |
|           |                  | C3-C4-O-H = 0.0 | | |
| c1.1 | ![Chemical Structure](image) | $C_s$ | $-534.763544 (0.0)$ | $-534.651122 (0.0)$ |
|------|----------------------------|------|---------------------|---------------------|
|      |                            |      | C2-C1-C(H)=O = 0.0  |                     |
|      |                            |      | C2-C3-O-C(H$_3$) = 0.0 |                   |
|      |                            |      | C3-C4-O-H = 0.0    |                     |

| cs.2 | ![Chemical Structure](image) | $C_s$ | $-534.762495 (0.7)$ | $-534.650290 (0.5)$ |
|------|----------------------------|------|---------------------|---------------------|
|      |                            |      | C2-C1-C(H)=O = 180.0 |                     |
|      |                            |      | C2-C3-O-C(H$_3$) = 0.0 |                   |
|      |                            |      | C3-C4-O-H = 0.0    |                     |
Part 2. Cyanines derived from condensation of 1,4-benzothiazines with 4-(dimethylamino)benzaldehyde

Table 2.1. Parent benzothiazine: conformational exploration

| Isomer / conformer | Schematic drawing | Symmetry | Selected dihedrals / deg | $E$ or $G_{PCM}$ / hartree ($\Delta E$ or $\Delta G_{PCM}$ / kcal mol$^{-1}$) | $G_{RRHO}$ or $G_{PCM,RRHO}$ / hartree ($\Delta G_{RRHO}$ or $\Delta G_{PCM,RRHO}$ / kcal mol$^{-1}$) |
|--------------------|-------------------|----------|--------------------------|-------------------------------------------------|----------------------------------------------------------------------------------|
| Neutral form in vacuo |                  | $C_1$ |                           |                                                 |                                                                                  |
| $E, c1.1$          | ![Diagram](image1) |          |                          | $-1164.098441$ (3.3)                          | $-1163.854003$ (3.7)                                                               |
|                    |                   | $C_1$   |                          | $C4a$-$C8a$-$S$-$C2 = 22.0$                    | $C8a$-$S$-$C2$-$C(H) = 155.4$                                                 |
|                    |                   |         |                          | $S$-$C2$-$C(H)$-$C1' = 177.2                   | $C2$-$C(H)$-$C1'-$C2' = 32.3                                                   |
|                    |                   |         |                          | $C3'$-$C4'$-$N$-$C(H_3) = 7.8                  | $C3'$-$C4'$-$N$-$C(H_3) = 169.9                                                |
| $E, c1.2$          | ![Diagram](image2) | $C_1$   |                          | $-1164.098314$ (3.4)                          | $-1163.854887$ (3.1)                                                               |
|                    |                   |         |                          | $C4a$-$C8a$-$S$-$C2 = 22.1$                    | $C8a$-$S$-$C2$-$C(H) = 155.2                                                  |
|                    |                   |         |                          | $S$-$C2$-$C(H)$-$C1' = 177.2                   | $C2$-$C(H)$-$C1'-$C2' = 32.2                                                   |
| Configuration | Image | Bond Angles and Distances | Energy | Energy Error |
|---------------|-------|--------------------------|--------|-------------|
| Z, cs.1 | ![S105](image1.png) | C₈: C4a-C8a-S-C2 = 0.0, C8a-S-C2-C(H) = 180.0, S-C2-C(H)-C1' = 0.0, C2-C(H)-C1'-C2' = 0.0, C3'-C4'-N-C(H₃) = 0.0, C3'-C4'-N-C(H₃) = 180.0 | -1164.103742 (0.0) | -1163.859549 (0.2) |
| Z, c1.1 | ![S105](image2.png) | C₈: C4a-C8a-S-C2 = 0.2, C8a-S-C2-C(H) = 179.7, S-C2-C(H)-C1' = -0.1, C2-C(H)-C1'-C2' = 0.9, C3'-C4'-N-C(H₃) = 6.9, C3'-C4'-N-C(H₃) = 173.0 | -1164.103723 (0.0) | -1163.859892 (0.0) |
| $Z$, c1.2 | approx. $C_2$ | Neutral form in methanol | E, c1.1 |
|---|---|---|---|
| ![Structure](image) | C4a-C8a-S-C2 = 0.0  
C8a-S-C2-C(H) = 180.0  
S-C2-C(H)-C1' = 0.0  
C2-C(H)-C1'-C2' = -0.1  
C3'-C4'-N-C(H3) = -0.5  
C3'-C4'-N-C(H3) = 179.5 | -1164.103699 (0.0) | ![Structure](image)  
C4a-C8a-S-C2 = 23.7  
C8a-S-C2-C(H) = 153.9  
S-C2-C(H)-C1' = 177.1  
C2-C(H)-C1'-C2' = 29.1  
C3'-C4'-N-C(H3) = 5.1  
C3'-C4'-N-C(H3) = 172.5 | -1164.109167 (3.8) | -1163.865137 (4.2) |
| $Z, \text{ cs.1}$ | ![Molecule](image1.png) | $C_2$ |
| --- | --- | --- |
| $C4a\text{-}C8a\text{-}S\text{-}C2 = 0.0$ | -1164.115160 (0.0) | saddle point |
| $C8a\text{-}S\text{-}C2\text{-}C(H) = 180.0$ |
| $S\text{-}C2\text{-}(H)\text{-}C1' = 0.0$ |
| $C2\text{-}(H)\text{-}C1'\text{-}C2' = 0.0$ |
| $C3'\text{-}C4'\text{-}N\text{-}C(H_3) = 0.0$ |
| $C3'\text{-}C4'\text{-}N\text{-}C(H_3) = 180.0$ |

| $Z, \text{ c1.1}$ | ![Molecule](image2.png) | $C_2$ |
| --- | --- | --- |
| $C4a\text{-}C8a\text{-}S\text{-}C2 = 0.0$ | -1164.115120 (0.0) | -1163.871903 (0.0) |
| $C8a\text{-}S\text{-}C2\text{-}C(H) = 179.9$ |
| $S\text{-}C2\text{-}(H)\text{-}C1' = 0.0$ |
| $C2\text{-}(H)\text{-}C1'\text{-}C2' = 0.1$ |
| $C3'\text{-}C4'\text{-}N\text{-}C(H_3) = 0.5$ |
| $C3'\text{-}C4'\text{-}N\text{-}C(H_3) = 179.5$ |

**Monoprotonated (ammonium) form in methanol**

| $E, \text{ c1.1}$ | ![Molecule](image3.png) | $C_2$ |
| --- | --- | --- |
| $C4a\text{-}C8a\text{-}S\text{-}C2 = 18.5$ | -1164.547065 (12.0) | -1164.286395 (13.7) |
| $C8a\text{-}S\text{-}C2\text{-}C(H) = 159.6$ |
| $S\text{-}C2\text{-}(H)\text{-}C1' = 177.1$ |
| Structure | Symmetry  | C2-C(H)-C1'-C2' = 36.9 | C3'-C4'-N-C(H3) = 115.9 | C3'-C4'-N-C(H3) = -116.6 |
|-----------|-----------|------------------------|-------------------------|--------------------------|
| E, c1.2   | $C_1$     | C4a-C8a-S-C2 = 17.7    | C8a-S-C2-C(H) = 161.1   | S-C2-C(H)-C1' = 177.0    |
|           |           | C2-C(H)-C1'-C2' = 38.2 |                         |                          |
|           |           | C3'-C4'-N-C(H3) = 121.2 |                         |                          |
|           |           | C3'-C4'-N-C(H3) = -111.3 |                         |                          |
| Z, cs.1   | $C_1$     | C4a-C8a-S-C2 = 0.0     | C8a-S-C2-C(H) = 180.0   | S-C2-C(H)-C1' = 0.0      |
|           |           | C2-C(H)-C1'-C2' = 0.0  |                         |                          |
|           |           | C3'-C4'-N-C(H3) = 116.2 |                         |                          |
|           |           | C3'-C4'-N-C(H3) = -116.2 |                         |                          |

**Saddle point**
### Monoprotonated (iminium) form in methanol

| Configuration | Structure | Approx. $C_i$ | $E_{	ext{c1.1}}$ | $E_{	ext{c1.2}}$ |
|---------------|-----------|---------------|-----------------|-----------------|
| **Z, c1.1**   | ![Structure Z, c1.1](image) | approx. $C_i$ | -1164.552221 (8.8) | -1164.292172 (10.1) |
|               |           | C4a-C8a-S-C2  = 0.5 |                 |                  |
|               |           | C8a-S-C2-C(H) = 179.5 |                 |                  |
|               |           | S-C2-C(H)-C1' = 0.3 |                 |                  |
|               |           | C2-C(H)-C1'·C2' = 1.5 |                 |                  |
|               |           | C3'·C4'·N-C(H) = 116.8 |                 |                  |
|               |           | C3'·C4'·N-C(H) = -115.8 |               |                  |
| **Z, c1.2**   | ![Structure Z, c1.2](image) | $C_i$         | -1164.552181 (8.8) | -1164.291714 (10.4) |
|               |           | C4a-C8a-S-C2  = 2.9 |                 |                  |
|               |           | C8a-S-C2-C(H) = 176.1 |                 |                  |
|               |           | S-C2-C(H)-C1' = -1.0 |               |                  |
|               |           | C2-C(H)-C1'·C2' = 8.2 |               |                  |
|               |           | C3'·C4'·N-C(H) = 119.8 |               |                  |
|               |           | C3'·C4'·N-C(H) = -112.9 |           |                  |

**E, c1.1**

| Structure | $C_i$ | $E_{	ext{c1.1}}$ | $E_{	ext{c1.2}}$ |
|-----------|-------|-----------------|-----------------|
| ![Structure E, c1.1](image) | $C_i$ | -1164.557647 (5.4) | -1164.299124 (5.7) |
|           | C4a-C8a-S-C2  = 25.4 |                  |                  |
|           | C8a-S-C2-C(H) = 159.6 |                  |                  |
|           | S-C2-C(H)-C1' = -174.8 |               |                  |
| Structure | C2-C(H)-C1'-C2' = 22.8 | C3'-C4'-N-C(H3) = -1.5 | C3'-C4'-N-C(H3) = 176.0 |
|-----------|------------------------|------------------------|------------------------|

| $\epsilon$, c1.2 | $E$, c1.2 |
|-----------------|----------------|
| ![Structure](image1.png) | ![Structure](image2.png) |
| C2 | C1 |
| C4a-C8a-S-C2 = 17.7 | C4a-C8a-S-C2 = 17.7 |
| C8a-S-C2-C(H) = 160.6 | C8a-S-C2-C(H) = 160.6 |
| S-C2-C(H)-C1' = 155.8 | S-C2-C(H)-C1' = 155.8 |
| C2-C(H)-C1'-C2' = -19.2 | C2-C(H)-C1'-C2' = -19.2 |
| C3'-C4'-N-C(H3) = 1.1 | C3'-C4'-N-C(H3) = 1.1 |
| C3'-C4'-N-C(H3) = -176.6 | C3'-C4'-N-C(H3) = -176.6 |
| Energy: -1164.557895 (5.2) | Energy: -1164.299238 (5.7) |

| $Z$, cs.1 |
|-----------|
| ![Structure](image3.png) |
| C2 | C1 |
| C4a-C8a-S-C2 = 0.0 | C4a-C8a-S-C2 = 0.0 |
| C8a-S-C2-C(H) = 180.0 | C8a-S-C2-C(H) = 180.0 |
| S-C2-C(H)-C1' = 0.0 | S-C2-C(H)-C1' = 0.0 |
| C2-C(H)-C1'-C2' = 0.0 | C2-C(H)-C1'-C2' = 0.0 |
| C3'-C4'-N-C(H3) = 0.0 | C3'-C4'-N-C(H3) = 0.0 |
| C3'-C4'-N-C(H3) = 180.0 | C3'-C4'-N-C(H3) = 180.0 |
| Energy: -1164.566178 (0.0) | Energy: -1164.308240 (0.0) |
| Geometry | Energy (hartrees) | Z, c1.1 |
|----------|------------------|---------|
|          |                  | ![Structure](image) |
|          |                  | C4a-C8a-S-C2 = 4.0 |
|          |                  | C8a-S-C2-C(H) = 176.4 |
|          |                  | S-C2-C(H)-C1' = -1.5 |
|          |                  | C2-C(H)-C1'-C2' = 0.4 |
|          |                  | C3'-C4'-N-C(H3) = -0.4 |
|          |                  | C3'-C4'-N-C(H3) = 179.5 |
|          | -1164.566123 (0.0) | -1164.307855 (0.2) |

**Diprotonated form in methanol**

| Geometry | Energy (hartrees) | E, c1.1 |
|----------|------------------|---------|
|          |                  | ![Structure](image) |
|          |                  | C4a-C8a-S-C2 = 20.0 |
|          |                  | C8a-S-C2-C(H) = 161.5 |
|          |                  | S-C2-C(H)-C1' = 178.1 |
|          |                  | C2-C(H)-C1'-C2' = 38.6 |
|          |                  | C3'-C4'-N-C(H3) = 120.5 |
|          |                  | C3'-C4'-N-C(H3) = -112.1 |
|          | -1164.981741 (4.1) | -1164.706048 (5.5) |

| Geometry | Energy (hartrees) | E, c1.2 |
|----------|------------------|---------|
|          |                  | ![Structure](image) |
|          |                  | C4a-C8a-S-C2 = 10.6 |
|          |                  | C8a-S-C2-C(H) = 166.4 |
|          |                  | S-C2-C(H)-C1' = 167.4 |
|          | -1164.981369 (4.4) | -1164.706762 (5.0) |
| Z, cs.1 |  |  |
|---|---|---|
| ![Chemical Structure](image1) | C2-C(H)-C1'-C2' = -38.3  
C3'-C4'-N-C(H3) = 114.4  
C3'-C4'-N-C(H3) = -118.4 | -1164.988311 (0.0) saddle point |
| Z, c1.1 |  |  |
| ![Chemical Structure](image2) | C2-C(H)-C1'-C2' = 5.8  
C8a-S-C2-C(H) = 173.4  
S-C2-C(H)-C1' = -2.5  
C2-C(H)-C1'-C2' = 7.5  
C3'-C4'-N-C(H3) = 119.1  
C3'-C4'-N-C(H3) = -113.6 | -1164.988229 (0.1)  
-1164.713168 (1.1) |
| Z, c1.2 | C₂ | C4a-C8a-S-C2 = 1.8  
|        |    | C8a-S-C2-C(H) = 178.1  
|        |    | S-C2-C(H)-C1’ = -1.8  
|        |    | C2-C(H)-C1’-C2’ = -2.3  
|        |    | C3’-C4’-N-C(H₃) = 115.9  
|        |    | C3’-C4’-N-C(H₃) = -116.9  
|        |    |  |
| Z, c1.3 | C₂ | C4a-C8a-S-C2 = 4.0  
|        |    | C8a-S-C2-C(H) = 175.8  
|        |    | S-C2-C(H)-C1’ = -1.6  
|        |    | C2-C(H)-C1’-C2’ = 3.4  
|        |    | C3’-C4’-N-C(H₃) = 116.2  
|        |    | C3’-C4’-N-C(H₃) = -116.6  
|        |    |  |

**Figure 2.1.** Parent benzothiazine: TD-PBE0 calculations
DMABA, parent benzothiazine
monoprotonated (ammonium) form in methanol

DMABA, parent benzothiazine
monoprotonated (iminium) form in methanol
Figure 2.2. Parent benzothiazine: TD-M06-2X calculations
Table 2.2. 3-Methylbenzothiazine: conformational exploration

| Isomer / conformer | Schematic drawing | Symmetry | $E$ or $G_{\text{PCM}}$ / hartree | $G_{\text{RRHO}}$ or $G_{\text{PCM,RRHO}}$ / hartree |
|--------------------|-------------------|----------|---------------------------------|---------------------------------|
|                    |                   |          | (Δ$E$ or Δ$G_{\text{PCM}}$ / kcal mol$^{-1}$) | (Δ$G_{\text{RRHO}}$ or Δ$G_{\text{PCM,RRHO}}$ / kcal mol$^{-1}$) |
| Neutral form in vacuo |                  |          |                                  |                                  |
|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |
| $E$, c1.1 |  |  |  |  |  |  |
| ![Diagram](image) | $C_s$ |  |  |  |  |  |
|  | C4a-C8a-S-C2 = 28.2 |  |  |  |  |  |
|  | C8a-S-C2-C(H) = 131.5 |  |  |  |  |  |
|  | S-C2-(H)-C1' = -176.6 |  |  |  |  |  |
|  | C2-(H)-C1'-C2' = 31.1 |  |  |  |  |  |
|  | C3'-C4'-N-C(H$_3$) = 8.0 |  |  |  |  |  |
|  | C3'-C4'-N-C(H$_3$) = 170.2 |  |  |  |  |  |
|  | -1203.369253 (4.0) |  |  |  |  |  |
|  | -1203.098565 (4.3) |  |  |  |  |  |
|  |  |  |  |  |  |  |
| $Z$, cs.1 |  |  |  |  |  |  |
| ![Diagram](image) | $C_s$ |  |  |  |  |  |
|  | C4a-C8a-S-C2 = 0.0 |  |  |  |  |  |
|  | C8a-S-C2-C(H) = 180.0 |  |  |  |  |  |
|  | S-C2-(H)-C1' = 0.0 |  |  |  |  |  |
|  | C2-(H)-C1'-C2' = 0.0 |  |  |  |  |  |
|  | C3'-C4'-N-C(H$_3$) = 0.0 |  |  |  |  |  |
|  | C3'-C4'-N-C(H$_3$) = 180.0 |  |  |  |  |  |
|  | -1203.375415 (0.1) |  |  |  |  |  |
|  | saddle point |  |  |  |  |  |
|  |  |  |  |  |  |  |
| $Z$, c1.1 |  |  |  |  |  |  |
| ![Diagram](image) | $C_s$ |  |  |  |  |  |
|  | C4a-C8a-S-C2 = 13.5 |  |  |  |  |  |
|  | C8a-S-C2-C(H) = 163.5 |  |  |  |  |  |
|  | S-C2-(H)-C1' = -4.2 |  |  |  |  |  |
|  | C2-(H)-C1'-C2' = 11.0 |  |  |  |  |  |
|  | -1203.375573 (0.0) |  |  |  |  |  |
|  | -1203.105463 (0.0) |  |  |  |  |  |

S120
| $E$, c1.1 | $E$, c1.2 |
|---|---|
| ![Diagram](image1) | ![Diagram](image2) |
| $C_1$ | $C_2$ |
| C4a-C8a-S-C2 = 29.1 | C4a-C8a-S-C2 = 24.5 |
| C8a-S-C2-C(H) = 130.5 | C8a-S-C2-C(H) = 138.1 |
| S-C2-C(H)-C1' = -176.3 | S-C2-C(H)-C1' = 166.7 |
| C2-C(H)-C1'-C2' = 28.1 | C2-C(H)-C1'-C2' = -54.6 |
| C3'-C4'-N-C(H$_3$) = 5.3 | C3'-C4'-N-C(H$_3$) = -8.5 |
| C3'-C4'-N-C(H$_3$) = 172.4 | C3'-C4'-N-C(H$_3$) = -170.6 |
| -1203.379838 (4.3) | -1203.374083 (7.9) |
| -1203.109734 (4.5) | -1203.104375 (7.9) |

Neutral form in methanol
| Configuration | Structure | Conformational Angles | Energy (kcal/mol) | Description |
|---------------|-----------|----------------------|------------------|-------------|
| Z, cs.1       | ![Structure Z, cs.1](image) | C1  
C4a-C8a-S-C2 = 0.0  
C8a-S-C2-C(H) = 180.0  
S-C2-C(H)-C1′ = 0.0  
C2-C(H)-C1′-C2′ = 0.0  
C3′-C4′-N-C(H3) = 0.0  
C3′-C4′-N-C(H3) = 180.0 | $-1203.386511 \pm 0.1$ | saddle point |
| Z, c1.1       | ![Structure Z, c1.1](image) | C1  
C4a-C8a-S-C2 = 16.0  
C8a-S-C2-C(H) = 160.6  
S-C2-C(H)-C1′ = -4.5  
C2-C(H)-C1′-C2′ = 11.6  
C3′-C4′-N-C(H3) = 3.9  
C3′-C4′-N-C(H3) = 174.8 | $-1203.386705 \pm 0.0$ | $-1203.116961 \pm 0.0$ |

**Monoprotonated (ammonium) form in methanol**

| Configuration | Structure | Conformational Angles | Energy (kcal/mol) | Description |
|---------------|-----------|----------------------|------------------|-------------|
| E, c1.1       | ![Structure E, c1.1](image) | C1  
C4a-C8a-S-C2 = 27.0  
C8a-S-C2-C(H) = 133.5  
S-C2-C(H)-C1′ = -177.6 | $-1203.817545 \pm 13.6$ | $-1203.530505 \pm 15.0$ |
|  |  | C2-C(H)-C1’-C2’ = 36.6  
  |  | C3’-C4’-N-C(H₃) = 113.9  
  |  | C3’-C4’-N-C(H₃) = -118.6  |
|---|---|---|
| $\varepsilon$, c1.2 | $C_1$  
|  | C4a-C8a-S-C2 = 26.7  
|  | C8a-S-C2-C(H) = 133.9  
|  | S-C2-C(H)-C1’ = -178.4  
|  | C2-C(H)-C1’-C2’ = 35.9  
|  | C3’-C4’-N-C(H₃) = 66.5  
|  | C3’-C4’-N-C(H₃) = -60.9  | -1203.817506 (13.6)  
|  |  | -1203.530559 (15.0)  |
| $Z$, cs.1 | $C_1$  
|  | C4a-C8a-S-C2 = 0.0  
|  | C8a-S-C2-C(H) = 180.0  
|  | S-C2-C(H)-C1’ = 0.0  
|  | C2-C(H)-C1’-C2’ = 0.0  
|  | C3’-C4’-N-C(H₃) = 116.4  
|  | C3’-C4’-N-C(H₃) = -116.4  | -1203.824311 (9.3)  
|  |  | -1203.533282 (13.3)  |
| Z, c1.1 | ![Structure](image1) | \( C_2 \) | \(-1203.824610 \text{ (9.1)}\) | \(-1203.537211 \text{ (10.8)}\) |
|---|---|---|---|---|
| \( C_4a\text{-}C_8a\text{-}S\text{-}C_2 = 12.6 \) | \( C_8a\text{-}S\text{-}C_2\text{-}C(H) = 162.1 \) |
| \( S\text{-}C_2\text{(H)}\text{-}C1' = -4.3 \) | \( C_2\text{(H)}\text{-}C1'\text{-}C2' = 23.4 \) |
| \( C3'\text{-}C4'\text{'\text{-}N\text{-}(H_3) = 118.4 \) | \( C3'\text{-}C4'\text{'\text{-}N\text{-}(H_3) = -114.1 \) |

| Monoprotonated (iminium) form in methanol |
|---|---|---|---|---|
| \( E, c1.1 \) | ![Structure](image2) | \( C_2 \) | \(-1203.828166 \text{ (6.9)}\) | \(-1203.543640 \text{ (6.8)}\) |
| \( C_4a\text{-}C_8a\text{-}S\text{-}C_2 = 34.1 \) | \( C_8a\text{-}S\text{-}C_2\text{-}C(H) = 139.3 \) |
| \( S\text{-}C_2\text{(H)}\text{-}C1' = -171.4 \) | \( C_2\text{(H)}\text{-}C1'\text{-}C2' = 24.2 \) |
| \( C3'\text{-}C4'\text{'\text{-}N\text{-}(H_3) = -1.2 \) | \( C3'\text{-}C4'\text{'\text{-}N\text{-}(H_3) = 176.4 \) |

| \( E, c1.2 \) | ![Structure](image3) | \( C_2 \) | \(-1203.827696 \text{ (7.2)}\) | saddle point |
|---|---|---|---|---|
| \( C_4a\text{-}C_8a\text{-}S\text{-}C_2 = 26.7 \) | \( C_8a\text{-}S\text{-}C_2\text{-}C(H) = 150.0 \) |
| \( S\text{-}C_2\text{(H)}\text{-}C1' = 143.4 \) | |
|   |   | Bond Angles (deg) | Energy (kcal/mol) |
|---|---|------------------|------------------|
| $E$, c1.3 | $C_1$ | C2-C(H)-C1' = 143.3 | -1203.827698 (7.2) |
|   |   | C2-C(H)-C1' = -20.3 | -1203.542654 (7.4) |
|   |   | C3'-C4' - N-C(H$_3$) = 1.8 |  |
|   |   | C3'-C4' - N-C(H$_3$) = -176.5 |  |
| $Z$, cs.1 | $C_1$ | C4a-C8a-S-C2 = 0.0 | -1203.838984 (0.1) |
|   |   | C8a-S-C2-C(H) = 180.0 | saddle point |
|   |   | S-C2-C(H)-C1' = 0.0 |  |
|   |   | C2-C(H)-C1' = 0.0 |  |
|   |   | C3'-C4' - N-C(H$_3$) = 0.0 |  |
|   |   | C3'-C4' - N-C(H$_3$) = 180.0 |  |
| Structure | $Z$, c1.1 | $E$, c1.1 | Diprotonated form in methanol |
|-----------|-----------|-----------|-------------------------------|
| ![Structure](image) | ![Structure](image) | ![Structure](image) | -1203.839146 (0.0) |
| | C4a-C8a-S-C2 = 21.1 | C4a-C8a-S-C2 = 30.8 | -1204.255041 (5.5) |
| | C8a-S-C2-C(H) = 159.7 | C8a-S-C2-C(H) = 133.1 | -1204.954373 (5.5) |
| | S-C2-C(H)-C1' = -6.0 | S-C2-C(H)-C1' = -178.4 | |
| | C2-C(H)-C1'-C2' = 3.3 | C2-C(H)-C1'-C2' = 35.4 | |
| | C3'-C4'-N-C(H$_3$) = -0.7 | C3'-C4'-N-C(H$_3$) = 114.4 | |
| | C3'-C4'-N-C(H$_3$) = 179.0 | C3'-C4'-N-C(H$_3$) = -118.1 | |
| | ![Structure](image) | ![Structure](image) | -1203.554446 (0.0) |
| | C4a-C8a-S-C2 = 26.1 | C4a-C8a-S-C2 = 30.8 | -1204.252293 (7.2) |
| | C8a-S-C2-C(H) = 142.0 | C8a-S-C2-C(H) = 133.1 | -1203.952302 (6.8) |
| | S-C2-C(H)-C1' = 166.0 | S-C2-C(H)-C1' = 178.4 | |
| Isomer | Structure | Energies | Saddle Point |
|--------|----------|----------|--------------|
| **Z, cs.1** | ![Structure](image1) | C<sub>4</sub>  
C4a-C8a-S-C2 = 0.0  
C8a-S-C2-C(H) = 180.0  
S-C2-C(H)-C1' = 0.0  
C2-C(H)-C1'-C2' = 0.0  
C3'-C4'-N-C(H<sub>3</sub>) = 118.9  
C3'-C4'-N-C(H<sub>3</sub>) = -118.9 | -1204.263257 (0.3) | saddle point |
| **Z, cs.2** | ![Structure](image2) | C<sub>4</sub>  
C4a-C8a-S-C2 = 0.0  
C8a-S-C2-C(H) = 180.0  
S-C2-C(H)-C1' = 0.0  
C2-C(H)-C1'-C2' = 0.0  
C3'-C4'-N-C(H<sub>3</sub>) = 118.9  
C3'-C4'-N-C(H<sub>3</sub>) = -118.9 | -1204.259785 (2.5) | saddle point |
| $Z, c1.1$ | $Z, c1.2$ | \( C_2 \) |
| --- | --- | --- |
| 
| 
| C4a-C8a-S-C2 = 17.2 |
| C8a-S-C2-C(H) = 159.4 |
| S-C2-C(H)-C1' = -5.3 |
| C2-C(H)-C1'-C2' = 22.8 |
| C3'-C4'-N-C(H3) = 118.2 |
| C3'-C4'-N-C(H3) = -114.3 |
| -1204.263793 (0.0) |
| -1203.961477 (1.1) |

| $Z, c1.1$ | $Z, c1.2$ | \( C_2 \) |
| --- | --- | --- |
| 
| 
| C4a-C8a-S-C2 = 17.0 |
| C8a-S-C2-C(H) = 160.6 |
| S-C2-C(H)-C1' = -6.3 |
| C2-C(H)-C1'-C2' = 13.5 |
| C3'-C4'-N-C(H3) = 113.0 |
| C3'-C4'-N-C(H3) = -119.6 |
| 1204.263595 (0.1) |
| 1203.963212 (0.0) |

Table 2.3. 3-Methylbenzothiazine: electronic transitions [TD-PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)] for the most stable structures identified, and isodensity maps (0.04 a.u.) of selected molecular orbitals.
| Isomer / conformer | Schematic drawing | \( \lambda / \text{nm} (f): \text{orbitalic contribution (expansion coefficient)}^b \) |
|--------------------|-------------------|-------------------------------------------------|
| **Neutral form in methanol** | | |
| Z, c1.1 | ![Schematic Drawing](image) | 448.9 (0.58): 78 \( \rightarrow \) 79 (0.69) |
| | | 331.9 (0.42): 78 \( \rightarrow \) 80 (0.67) |
| | | 322.1 (0.28): 76 \( \rightarrow \) 79 (0.12); 77 \( \rightarrow \) 79 (0.66); 78 \( \rightarrow \) 81 (0.12) |
| | | 308.4 (0.05): 76 \( \rightarrow \) 79 (0.22); 77 \( \rightarrow \) 79 (-0.18); 77 \( \rightarrow \) 81 (0.11); 78 \( \rightarrow \) 81 (0.62) |
| | | 301.7 (0.06): 74 \( \rightarrow \) 79 (-0.11); 75 \( \rightarrow \) 79 (-0.16); 76 \( \rightarrow \) 79 (-0.15); 78 \( \rightarrow \) 82 (0.64) |

#74, HOMO-4 (-0.27998)$^b$ #75, HOMO-3 (-0.27499) #76, HOMO-2 (-0.26029) #77, HOMO-1 (-0.23621) #78, HOMO (-0.19454)
S130

Monoprotonated (iminium) form in methanol

| #79, LUMO (-0.07071) | #80, LUMO+1 (-0.02879) | #81, LUMO+2 (-0.02007) | #82, LUMO+3 (-0.01216) | #83, LUMO+4 (-0.00328) |
|-----------------------|------------------------|------------------------|------------------------|------------------------|
| (isodensity level 0.016 a.u.) |

**Z, c1.1**

\[
\begin{align*}
H & \quad \text{(imidazole)} \\
\text{Me} & \quad \text{(methyl)} \\
\text{Me} & \quad \text{(methyl)} \\
\text{N} & \quad \text{(nitrogen)} \\
\text{S} & \quad \text{(sulfur)} \\
\text{Me} & \quad \text{(methyl)} \\
\text{N} & \quad \text{(nitrogen)} \\
\text{Me} & \quad \text{(methyl)} \\
\end{align*}
\]

\[
\begin{align*}
549.1 \ (0.65): & \quad 77 \rightarrow 79 \ (0.14) \ ; \ 78 \rightarrow 79 \ (0.69) \\
379.7 \ (0.32): & \quad 76 \rightarrow 79 \ (0.11) \ ; \ 77 \rightarrow 79 \ (0.68) \ ; \ 78 \rightarrow 79 \ (-0.13) \\
335.6 \ (0.44): & \quad 77 \rightarrow 80 \ (0.11) \ ; \ 78 \rightarrow 80 \ (0.67) \\
314.5 \ (0.05): & \quad 76 \rightarrow 79 \ (0.55) \ ; \ 78 \rightarrow 80 \ (0.11) \ ; \ 78 \rightarrow 81 \ (0.39) \\
311.0 \ (0.00): & \quad 75 \rightarrow 79 \ (0.67) \ ; \ 78 \rightarrow 82 \ (0.19)
\end{align*}
\]
#74, HOMO-4 (-0.31136)
#75, HOMO-3 (-0.29154)
#76, HOMO-2 (-0.28579)
#77, HOMO-1 (-0.25578)
#78, HOMO (-0.21481)

#79, LUMO (-0.11366)
#80, LUMO+1 (-0.04839)
#81, LUMO+2 (-0.03774)
#82, LUMO+3 (-0.02426)
#83, LUMO+4 (-0.00835)

(isodensity level 0.016 a.u.)

Diprotonated form in methanol
$Z, c1.1$

\[
\begin{align*}
497.0 (0.26): & \ 78 \rightarrow 79 (0.70) \\
343.0 (0.16): & \ 77 \rightarrow 79 (0.68); \ 78 \rightarrow 80 (0.17) \\
309.8 (0.38): & \ 76 \rightarrow 79 (0.38); \ 77 \rightarrow 79 (-0.16); \ 78 \rightarrow 80 (0.56) \\
304.9 (0.10): & \ 75 \rightarrow 79 (0.36); \ 76 \rightarrow 79 (0.47); \ 78 \rightarrow 80 (-0.32); \ 78 \rightarrow 81 (-0.17)
\end{align*}
\]

$\#74, \text{HOMO}-4 (-0.34235)$

$\#75, \text{HOMO}-3 (-0.31256)$

$\#76, \text{HOMO}-2 (-0.31074)$

$\#77, \text{HOMO}-1 (-0.29552)$

$\#78, \text{HOMO} (-0.25068)$
Only transitions above 300 nm are reported. Transitions with $f > 0.1$ and their main contributions are highlighted.

[b] Orbital energies in hartrees.

Figure 2.3. 3-Methylbenzothiazine: plot of selected orbital energies [PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)]
Figure 2.4. 3-Methylbenzothiazine: TD-PBE0 calculations
Figure 2.5. 3-Methylbenzothiazine: TD-M06-2X calculations
DMABA, 3-methylbenzothiazine

neutral form in vacuo

DMABA, 3-methylbenzothiazine

neutral form in methanol

absorbance, arbitrary units

wavelength, nm
Table 2.4. 3-Phenylbenzothiazine: conformational exploration

| Isomer / conformer | Schematic drawing | Symmetry | $E$ or $G_{PCM}$ / hartree | $E_{RRHO}$ or $G_{PCM,RRHO}$ / hartree |
|--------------------|-------------------|----------|----------------------------|----------------------------------------|
|                    |                   |          | ($\Delta E$ or $\Delta G_{PCM}$ / kcal mol$^{-1}$) | ($\Delta G_{RRHO}$ or $\Delta G_{PCM,RRHO}$ / kcal mol$^{-1}$) |
| Neutral form in vacuo |                   |          |                           |                                        |

DMABA, 3-methylbenzothiazine
diprotonated form in methanol
| Structure | Bond Lengths | Energy | Conformation |
|-----------|--------------|--------|--------------|
| **E, c1.1** | | | |
| ![Structure](image) | C4a-C8a·S-C2 = 28.6 <br> C8a·S-C2-C(H) = 126.7 <br> S-C2-C(H)-C1' = -178.0 <br> C2-C3-C1"-C2" = 18.1 <br> C2-C(H)-C1'-C2' = 25.0 <br> C3'-C4'-N-C(H3) = 7.7 <br> C3'-C4'-N-C(H3) = 171.0 | -1394.894736 (2.5) | saddle point |
| **E, c1.2** | | | |
| ![Structure](image) | C4a-C8a·S-C2 = 28.7 <br> C8a·S-C2-C(H) = 126.6 <br> S-C2-C(H)-C1' = -177.9 <br> C2-C3-C1"-C2" = 18.0 <br> C2-C(H)-C1'-C2' = 24.6 <br> C3'-C4'-N-C(H3) = -5.8 <br> C3'-C4'-N-C(H3) = -176.4 | -1394.894633 (2.5) | saddle point |
| Z, c1.1 | | | C₂ | | | -1394.898681 (0.0) | -1394.579796 (0.0) |
|---|---|---|---|---|---|---|---|
| ![Chemical Structure of Z, c1.1](image1) | C₄a-C₈a-S-C₂ = 22.3 | C₈a-S-C₂-C(H) = 143.5 | S-C₂-(H)-C₁' = -4.0 | C₂-C₃-C₁"-C₂" = 38.5 | C₂-(H)-C₁'-C₂' = 14.4 | C₃'-C₄'-N-(C(H₃)) = 7.1 | C₃'-C₄'-N-(C(H₃)) = 171.2 |
| Neutral form in methanol | | | | | | | |
| E, c1.1 | | | C₂ | | | -1394.906966 (2.6) | -1394.587697 (3.3) |
| ![Chemical Structure of E, c1.1](image2) | C₄a-C₈a-S-C₂ = 29.6 | C₈a-S-C₂-C(H) = 127.3 | S-C₂-(H)-C₁' = -177.4 | C₂-C₃-C₁"-C₂" = 22.6 | C₂-(H)-C₁'-C₂' = 25.9 | C₃'-C₄'-N-(C(H₃)) = 5.5 | C₃'-C₄'-N-(C(H₃)) = 173.2 |
|  |  | $Z, c1.1$ |  | $E, c1.1$ |  |
|---|---|---|---|---|---|
|  |  | ![Chemical Structure](image) | $C_2$ | $C_2$ |  |
|  |  |  | C4a-C8a-S-C2 = 23.4 | C4a-C8a-S-C2 = 35.7 |  |
|  |  |  | C8a-S-C2-C(H) = 143.4 | C8a-S-C2-C(H) = 132.7 |  |
|  |  |  | S-C2-C(H)-C1’ = -3.5 | S-C2-C(H)-C1’ = -171.8 |  |
|  |  |  | C2-C3-C1”-C2” = 41.4 | C2-C3-C1”-C2” = 34.6 |  |
|  |  |  | C2-C(H)-C1’-C2’ = 15.7 | C2-C(H)-C1’-C2’ = 22.7 |  |
|  |  |  | C3’-C4’-N-C(H3) = 3.7 | C3’-C4’-N-C(H3) = -0.6 |  |
|  |  |  | C3’-C4’-N-C(H3) = 174.7 | C3’-C4’-N-C(H3) = 176.9 |  |
|  |  |  |  |  |  |

Monoprotonated (iminium) form in methanol

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |

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| Structure | Charges | Bond Lengths (Å) | Diprotonated Form in Methanol | E, c1.2 | Z, c1.1 |
|-----------|---------|-----------------|-------------------------------|---------|---------|
| ![Structure E, c1.2](image) | +N+Me | C1-C4a-C8a-S-C2 = 25.5 | -1395.347808 (9.4) | -1395.014221 (9.4) | -1395.362781 (0.0) | -1395.029131 (0.0) |
| ![Structure Z, c1.1](image) | +N+Me | C1-C4a-C8a-S-C2 = 29.1 | -1395.347808 (9.4) | -1395.014221 (9.4) | -1395.362781 (0.0) | -1395.029131 (0.0) |

Diprotonated form in methanol
|       |       |       |       |       |       |
|-------|-------|-------|-------|-------|-------|
| **$E, \text{c1.1}$** | $C_2$ | C4a-C8a-S-C2 = 31.4 | C8a-S-C2-C(H) = 131.9 | S-C2-C(H)-C1' = 179.9 | C2-C3-C1"-C2" = 32.6 | C2-C(H)-C1'-C2' = 40.0 | C3'-C4'-N-C(H3) = 115.3 | C3'-C4'-N-C(H3) = -117.3 | **-1395.780267 (4.3)** | **-1395.431576 (3.4)** |
| **$Z, \text{c1.1}$** | $C_2$ | C4a-C8a-S-C2 = 25.8 | C8a-S-C2-C(H) = 143.0 | S-C2-C(H)-C1' = -3.9 | C2-C3-C1"-C2" = 44.3 | C2-C(H)-C1'-C2' = 28.1 | C3'-C4'-N-C(H3) = 117.8 | C3'-C4'-N-C(H3) = -114.8 | **-1395.787141 (0.0)** | **-1395.436404 (0.3)** |
Table 2.5. 3-Phenylbenzothiazine: electronic transitions [TD-PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)] for the most stable structures identified, and isodensity maps (0.04 a.u.) of selected molecular orbitals

| Isomer / conformer | Schematic drawing | $\lambda$ / nm ($f$): orbitalic contribution (expansion coefficient)\(^a\) |
|--------------------|-------------------|-------------------------------------------------|
| Neutral form in methanol |                  |                                                 |
$Z, c1.1$

\[
\begin{align*}
466.6 (0.34): & \quad 94 \rightarrow 95 (0.69) \\
348.6 (0.73): & \quad 93 \rightarrow 95 (-0.11); 94 \rightarrow 95 (-0.11); 94 \rightarrow 96 (0.67) \\
340.5 (0.15): & \quad 93 \rightarrow 95 (0.68); 94 \rightarrow 96 (0.12) \\
321.1 (0.09): & \quad 88 \rightarrow 95 (0.17); 89 \rightarrow 95 (0.12); 92 \rightarrow 95 (0.59); 94 \rightarrow 97 (0.27) \\
304.6 (0.02): & \quad 88 \rightarrow 95 (-0.16); 91 \rightarrow 95 (0.13); 92 \rightarrow 95 (-0.18); 94 \rightarrow 97 (0.57); 94 \rightarrow 99 (0.25)
\end{align*}
\]

#90, HOMO-4 (-0.27575)

#91, HOMO-3 (-0.27486)

#92, HOMO-2 (-0.25352)

#93, HOMO-1 (-0.23498)

#94, HOMO (-0.19802)
| #95, LUMO (-0.07603) | #96, LUMO+1 (-0.04154) | #97, LUMO+2 (-0.02224) | #98, LUMO+3 (-0.01798) | #99, LUMO+4 (-0.01270) |
|----------------------|------------------------|------------------------|------------------------|------------------------|
| **Monoprotonated (iminium) form in methanol** |
| $Z$, c1.1 |
| ![](image1.png) | ![](image2.png) | ![](image3.png) | ![](image4.png) |
| 562.5 (0.55): 93 → 95 (-0.15); 94 → 95 (0.68) |
| 400.8 (0.36): 93 → 95 (0.68); 94 → 95 (0.15) |
| 349.3 (0.44): 93 → 96 (-0.11); 94 → 96 (0.67) |
| 331.9 (0.24): 92 → 95 (0.68); 94 → 96 (-0.11); 94 → 97 (0.12) |
| 316.3 (0.01): 90 → 95 (-0.16); 91 → 95 (0.67); 94 → 100 (0.12) |
| 314.7 (0.00): 90 → 95 (0.68); 91 → 95 (0.15) |
| 304.4 (0.07): 89 → 95 (0.53); 94 → 97 (0.43) |
| #90, HOMO-4 (-0.29352) | #91, HOMO-3 (-0.29193) | #92, HOMO-2 (-0.28164) | #93, HOMO-1 (-0.25533) | #94, HOMO (-0.21804) |
|-------------------------|------------------------|------------------------|------------------------|------------------------|
| #95, LUMO (-0.11763)    | #96, LUMO+1 (-0.05983) | #97, LUMO+2 (-0.03891) | #98, LUMO+3 (-0.03487) | #99, LUMO+4 (-0.03148) |

Diprotonated form in methanol
S150
[a] Only transitions above 300 nm are reported. Transitions with $f > 0.1$ and their main contributions are highlighted.

[b] Orbital energies in hartrees.

Figure 2.6. 3-Phenylbenzothiazine: plot of selected orbital energies [PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)]
Figure 2.7. 3-Phenylbenzothiazine: TD-PBE0 calculations
Figure 2.8. 3-Phenylbenzothiazine: TD-M06-2X calculations
Part 3. Cyanines derived from condensation of 1,4-benzothiazines with 4-(dimethylamino)cinnamaldehyde

Table 3.1. 3-Methylbenzothiazine: conformational exploration

| Isomer / conformer | Schematic drawing | Symmetry | Selected dihedrals / deg | $\Delta E$ or $\Delta G_{\text{PCM}}$ / hartree (kcal mol$^{-1}$) | $G_{\text{RRHO}}$ or $G_{\text{PCM,RRHO}}$ / hartree (kcal mol$^{-1}$) |
|-------------------|------------------|----------|-------------------------|---------------------------------|---------------------------------|
| **Neutral form in vacuo** | | | | | |
| $E, \text{ap}, E, c1.1$ | | | | | |
| ![Schematic Drawing](image) | | | $C_2$ | -1280.688995 (4.5) | -1280.388353 (4.9) |
| | | | C4a-C8a-S-C2 = 24.4 | | |
| | | | C8a-S-C2-C(H) = 144.3 | | |
| | | | S-C2-C(H)-C(H) = 173.5 | | |
| | | | C2-C(H)-C(H)-C(H) = -179.8 | | |
| | | | C(H)-C(H)-C(H)-C1' = -179.5 | | |
| | | | C(H)-C(H)-C1'-C2' = 0.4 | | |
| | | | C3'-C4'-N-C(H$_3$) = 7.2 | | |
| | | | C3'-C4'-N-C(H$_3$) = 172.8 | | |
| $E, +sc, E, c1.1$ | $C_1$ | $-1280.681873 (8.9)$ | $-1280.381721 (9.0)$ |
|---|---|---|---|
| ![Chemical Structure](image) | C4a-C8a-S-C2 = 27.5  
C8a-S-C2-C(H) = 132.8  
S-C2-C(H)-C(H) = -176.2  
C2-C(H)-C(H)-C(H) = 31.5  
C(H)-C(H)-C(H)-C1' = 178.6  
C(H)-C(H)-C1'-C2' = 8.9  
C3'-C4'-N-C(H3) = 8.0  
C3'-C4'-N-C(H3) = 171.8 | | |

| $E, -sc, E, c1.1$ | $C_1$ | $-1280.677013 (12.0)$ | $-1280.377560 (11.6)$ |
|---|---|---|---|
| ![Chemical Structure](image) | C4a-C8a-S-C2 = 22.2  
C8a-S-C2-C(H) = 142.7  
S-C2-C(H)-C(H) = 163.1  
C2-C(H)-C(H)-C(H) = -50.2  
C(H)-C(H)-C(H)-C1' = -176.7  
C(H)-C(H)-C1'-C2' = -10.7  
C3'-C4'-N-C(H3) = 8.1  
C3'-C4'-N-C(H3) = 173.2 | | |
| Z, ap, E, c1.1 | $C_2$ | $-1280.696123 (0.0)$ | $-1280.396101 (0.0)$ |
|----------------|------------------|------------------|
| ![Chemical Structure](image) | C4a-C8a-S-C2 = 16.4 | | |
| | C8a-S-C2-C(H) = 160.9 | | |
| | S-C2-C(H)-C(H) = -7.4 | | |
| | C2-C(H)-C(H)-C(H) = 176.5 | | |
| | C(H)-C(H)-C(H)-C1' = 178.6 | | |
| | C(H)-C(H)-C1'-C2' = -0.6 | | |
| | C3'-C4'-N-C(H3) = 7.8 | | |
| | C3'-C4'-N-C(H3) = 173.0 | | |
| Z, sp, E, c1.1 | $C_1$ | $-1280.690222 (3.7)$ | $-1280.390062 (3.8)$ |
| ![Chemical Structure](image) | C4a-C8a-S-C2 = 10.3 | | |
| | C8a-S-C2-C(H) = 166.8 | | |
| | S-C2-C(H)-C(H) = -3.2 | | |
| | C2-C(H)-C(H)-C(H) = 12.5 | | |
| | C(H)-C(H)-C(H)-C1' = -178.7 | | |
| | C(H)-C(H)-C1'-C2' = 8.5 | | |
| | C3'-C4'-N-C(H3) = 8.4 | | |
| | C3'-C4'-N-C(H3) = 171.7 | | |
| Configuration | Structure | Bond Lengths (Å) | Energy (kcal/mol) |
|---------------|-----------|-----------------|------------------|
| Z, sp, E, c1.2 | ![Structure](image1.png) | C4a-C8a-S-C2 = 10.7, C8a-S-C2-C(H) = 166.3, S-C2-C(H)-C(H) = -3.2, C2-(C(H)-C(H)-C(H) = 13.1, C(H)-(C(H)-C(H)-C1' = -178.7, C(H)-(C(H)-C1'-C2' = 7.6, C3'-C4'-N-C(H3) = -8.8, C3'-C4'-N-C(H3) = -172.6 | -1280.690172 (3.7) -1280.390585 (3.5) |
| E, ap, Z, c1.1 | ![Structure](image2.png) | C4a-C8a-S-C2 = 24.5, C8a-S-C2-C(H) = 144.2, S-C2-C(H)-C(H) = 179.4, C2-(C(H)-C(H)-C(H) = -170.2, C(H)-(C(H)-C(H)-C1' = 9.2, C(H)-(C(H)-C1'-C2' = 29.4, C3'-C4'-N-C(H3) = 8.1, C3'-C4'-N-C(H3) = 170.4 | -1280.683971 (7.6) -1280.382993 (8.2) |
| $E, \alpha p, Z, c1.2$ | $E, +sc, Z, c1.1$ |
|----------------|----------------|
| ![Molecule 1](image1) | ![Molecule 2](image2) |
| $C_2$ | $C_2$ |
| C4a-C8a-S-C2 = 23.0 | C4a-C8a-S-C2 = 25.7 |
| C8a-S-C2-C(H) = 145.1 | C8a-S-C2-C(H) = 141.0 |
| S-C2-C(H)-C(H) = 167.6 | S-C2-C(H)-C(H) = 174.0 |
| C2-C(H)-C(H)-C(H) = 168.1 | C2-C(H)-C(H)-C(H) = 53.6 |
| C(H)-C(H)-C(H)-C1' = -7.9 | C(H)-C(H)-C(H)-C1' = 1.6 |
| C(H)-C(H)-C1’-C2’ = -29.6 | C(H)-C(H)-C1’-C2’ = 15.9 |
| C3’-C4’-N-C(H3) = -7.6 | C3’-C4’-N-C(H3) = 8.8 |
| C3’-C4’-N-C(H3) = -170.0 | C3’-C4’-N-C(H3) = 171.5 |

| $-1280.683840 (7.7)$ | $-1280.676238 (12.5)$ |
| $-1280.382256 (8.7)$ | $-1280.375692 (12.8)$ |
|   |   |   | \( Z, \text{ap}, Z, \text{c1.1} \) |   |   | \( Z, \text{ap}, Z, \text{c1.2} \) |
|---|---|---|-------------------------|---|---|-------------------------|
|   | ![Diagram](image-url) | \( C_1 \) | C4a-C8a-S-C2 = 15.6 | \( \text{H} \) | C4a-C8a-S-C2 = 15.6 |
|   |   | C8a-S-C2-C(H) = 161.6 |   | C8a-S-C2-C(H) = 161.7 |
|   |   | S-C2-C(H)-C(H) = -11.4 |   | S-C2-C(H)-C(H) = -11.4 |
|   |   | C2-C(H)-C(H)-C(H) = 169.5 |   | C2-C(H)-C(H)-C(H) = 169.5 |
|   |   | C(H)-C(H)-C(H)-C' = -9.3 |   | C(H)-C(H)-C(H)-C' = -9.3 |
|   |   | C(H)-C(H)-C'-'C' = -28.7 |   | C(H)-C(H)-C'-'C' = -28.6 |
|   |   | C3'-C4'-'N-C(H₃) = -8.5 |   | C3'-C4'-'N-C(H₃) = 7.0 |
|   |   | C3'-C4'-'N-C(H₃) = -170.2 |   | C3'-C4'-'N-C(H₃) = 174.7 |
|   |   | \(-1280.691885 \ (2.7)\) |   | \(-1280.691735 \ (2.8)\) |
|   |   | \(-1280.390707 \ (3.4)\) |   | \(-1280.392079 \ (2.5)\) |

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| Z, +sc, Z, c1.1 | ![Chemical Structure 1](image1.png) | \( C_2 \) | -1280.683216 (8.1) | -1280.381507 (9.2) |
| --- | --- | --- | --- | --- |
|  | C4a-C8a-S-C2 = 11.7 | S-C2-C(H)-C(H) = -5.6 | C(H)-C(H)-C1' = 12.4 | C(H)-C(H)-C1'-C2' = 16.4 |
|  | C8a-S-C2-C(H) = 163.7 | C2-C(H)-C(H)-C(H) = 45.5 | C(H)-C(H)-C(H)-C1 = 45.7 | C3'-C4'-N-C(H3) = 9.0 |
|  | S-C2-C(H)-C(H) = -5.6 | C(H)-C(H)-C1' = 12.5 | C(H)-C(H)-C1'-C2' = 16.1 | C3'-C4'-N-C(H3) = 170.5 |
|  | C2-C(H)-C(H)-C(H) = 45.5 | C(H)-C(H)-C1' = 12.4 | C(H)-C(H)-C1'-C2' = 16.4 | C3'-C4'-N-C(H3) = 9.0 |
|  | C(H)-C(H)-C1' = 12.4 | C(H)-C(H)-C1'-C2' = 16.4 | C3'-C4'-N-C(H3) = 170.5 | C3'-C4'-N-C(H3) = 170.5 |

| Z, +sc, Z, c1.2 | ![Chemical Structure 2](image2.png) | \( C_1 \) | -1280.683113 (8.2) | -1280.381889 (8.9) |
| --- | --- | --- | --- | --- |
|  | C4a-C8a-S-C2 = 11.9 | S-C2-C(H)-C(H) = -5.6 | C(H)-C(H)-C1' = 12.5 | C(H)-C(H)-C1'-C2' = 16.1 |
|  | C8a-S-C2-C(H) = 163.6 | C2-C(H)-C(H)-C(H) = 45.7 | C(H)-C(H)-C1' = 12.5 | C3'-C4'-N-C(H3) = -8.6 |
|  | S-C2-C(H)-C(H) = -5.6 | C(H)-C(H)-C1' = 12.5 | C(H)-C(H)-C1'-C2' = 16.1 | C3'-C4'-N-C(H3) = -172.7 |
|  | C2-C(H)-C(H)-C(H) = 45.7 | C(H)-C(H)-C1' = 12.5 | C(H)-C(H)-C1'-C2' = 16.1 | C3'-C4'-N-C(H3) = -172.7 |

Neutral form in methanol
| $E, \alpha p, E, c1.1$ | $C_2$ | -1280.701511 (4.4) | -1280.401877 (4.8) |
|---|---|---|---|
| ![Diagram](image) | C4a-C8a-S-C2 = 26.0  
C8a-S-C2-C(H) = 142.5  
S-C2-C(H)-C(H) = 173.7  
C2-C(H)-C(H)-C(H) = -179.7  
C(H)-C(H)-C(H)-C1' = -179.6  
C(H)-C(H)-C1'-C2' = -0.04  
C3'-C4'-N-C(H$_3$) = -0.2  
C3'-C4'-N-C(H$_3$) = 179.8 | |

| $E, +sc, E, c1.1$ | $C_2$ | -1280.693609 (9.3) | -1280.393845 (9.8) |
|---|---|---|---|
| ![Diagram](image) | C4a-C8a-S-C2 = 28.6  
C8a-S-C2-C(H) = 131.6  
S-C2-C(H)-C(H) = -175.9  
C2-C(H)-C(H)-C(H) = 30.1  
C(H)-C(H)-C(H)-C1' = 178.5  
C(H)-C(H)-C1'-C2' = 7.4  
C3'-C4'-N-C(H$_3$) = 3.5  
C3'-C4'-N-C(H$_3$) = 175.7 | |
| $E, \cdot sc, E, c1.1$ | $C_{z}$ | $\Delta$H | $\Delta$G |
|---|---|---|---|
| ![Chemical Structure](image1) | C4a-C8a-S-C2 = 24.2  
C8a-S-C2-C(H) = 138.5  
S-C2-C(H)-C(H) = 165.3  
C2-C(H)-C(H)-C(H) = -49.3  
C(H)-C(H)-C(H)-C1’ = -176.0  
C(H)-C(H)-C1’-C2’ = -7.7  
C3’-C4’-N-C(H$_3$) = 4.1  
C3’-C4’-N-C(H$_3$) = 176.2 | -1280.688605 (12.4) | -1280.388871 (13.0) |

| $Z, ap, E, c1.1$ | $C_{z}$ | $\Delta$H | $\Delta$G |
|---|---|---|---|
| ![Chemical Structure](image2) | C4a-C8a-S-C2 = 17.5  
C8a-S-C2-C(H) = 159.9  
S-C2-C(H)-C(H) = -7.1  
C2-C(H)-C(H)-C(H) = 177.2  
C(H)-C(H)-C(H)-C1’ = 178.8  
C(H)-C(H)-C1’-C2’ = -0.8  
C3’-C4’-N-C(H$_3$) = 1.4  
C3’-C4’-N-C(H$_3$) = 179.3 | -1280.708445 (0.0) | -1280.409535 (0.0) |
| Configuration | Structure | Bond Angles (°) | Energy (kcal/mol) |
|---------------|-----------|----------------|------------------|
| Z, sp, E, c1.1 | ![Structure](image1.png) | C4a-C8a-S-C2 = 12.3  
C8a-S-C2-C(H) = 164.4  
S-C2-C(H)-C(H) = -3.6  
C2-C(H)-C(H)-C(H) = 13.5  
C(H)-C(H)-C(H)-C1' = -178.8  
C(H)-C(H)-C1'-C2' = 5.9  
C3'-C4'-N-C(H3) = 4.0  
C3'-C4'-N-C(H3) = 175.8 | -1280.702329 (3.8) |
| E, ap, Z, c1.1 | ![Structure](image2.png) | C4a-C8a-S-C2 = 25.8  
C8a-S-C2-C(H) = 142.2  
S-C2-C(H)-C(H) = 179.5  
C2-C(H)-C(H)-C(H) = -171.2  
C(H)-C(H)-C(H)-C1' = 9.2  
C(H)-C(H)-C1'-C2' = 26.6  
C3'-C4'-N-C(H3) = 6.1  
C3'-C4'-N-C(H3) = 172.2 | -1280.695428 (8.2) |
| $E, ap, Z, c1.2$ | ![Chemical Structure](image1.png) | $C_2$ | $-1280.695093 (8.4)$ | $-1280.393630 (10.0)$ |
|---|---|---|---|---|
| $C4a$-$C8a$-$S$-$C2 = 24.4 | $C8a$-$S$-$C2$-$C(H) = 143.4 | $S$-$C2$-$C(H)$-$C(H) = 167.6 | $C2$-$C(H)$-$C(H)$-$C(H) = 169.4 | 
| $C(H)$-$C(H)$-$C(H)$-$C1' = -8.0 | $C(H)$-$C(H)$-$C1'$-$C2' = -27.4 | $C3'$-$C4'$-$N$-$C(H_3) = -5.7 | $C3'$-$C4'$-$N$-$C(H_3) = -171.9 |

| $E, +sc, Z, c1.1$ | ![Chemical Structure](image2.png) | $C_2$ | $-1280.687031 (13.4)$ | $-1280.386828 (14.2)$ |
|---|---|---|---|---|
| $C4a$-$C8a$-$S$-$C2 = 26.6 | $C8a$-$S$-$C2$-$C(H) = 139.0 | $S$-$C2$-$C(H)$-$C(H) = 174.4 | $C2$-$C(H)$-$C(H)$-$C(H) = 52.6 | 
| $C(H)$-$C(H)$-$C(H)$-$C1' = 2.1 | $C(H)$-$C(H)$-$C1'$-$C2' = 17.2 | $C3'$-$C4'$-$N$-$C(H_3) = 7.6 | $C3'$-$C4'$-$N$-$C(H_3) = 172.8 |
| Z, αp, Z, c1.1 | ![Chemical Structure](image) | **C**<sub>2</sub> | ΔH<sub>298</sub> = -1280.703170 (3.3) | ΔH<sub>298</sub> = -1280.402389 (4.5) |
|----------------|-----------------------------|-------------------|--------------------------------|--------------------------------|
|                | ![Chemical Structure](image) | C4a-C8a-S-C2 = 16.1 |                          |                              |
|                |                             | C8a-S-C2-C(H) = 161.1 |                          |                              |
|                |                             | S-C2-C(H)-C(H) = -11.2 |                          |                              |
|                |                             | C2-C(H)-C(H)-C(H) = 170.2 |                      |                              |
|                |                             | C(H)-C(H)-C(H)-C1' = -9.4 |                      |                              |
|                |                             | C(H)-C(H)-C1'-C2' = -25.4 |                      |                              |
|                |                             | C3'-C4'-N-C(H<sub>3</sub>) = -6.4 |                      |                              |
|                |                             | C3'-C4'-N-C(H<sub>3</sub>) = -172.7 |                      |                              |
| Z, +sc, Z, c1.1 | ![Chemical Structure](image) | C4a-C8a-S-C2 = 15.0 | -1280.694926 (8.5) | -1280.393615 (10.0) |
|                | ![Chemical Structure](image) | C8a-S-C2-C(H) = 159.5 |                          |                              |
|                |                             | S-C2-C(H)-C(H) = -6.0 |                          |                              |
|                |                             | C2-C(H)-C(H)-C(H) = 46.4 |                          |                              |
|                |                             | C(H)-C(H)-C(H)-C1' = 12.8 |                          |                              |
|                |                             | C(H)-C(H)-C1'-C2' = 16.6 |                          |                              |
|                |                             | C3'-C4'-N-C(H<sub>3</sub>) = 7.4 |                          |                              |
|                |                             | C3'-C4'-N-C(H<sub>3</sub>) = 172.8 |                          |                              |

Monoprotonated (iminium) form in methanol
| Configuration | Chemical Structure | References | Energy (kcal/mol) |
|---------------|--------------------|------------|------------------|
| $E$, $ap$, $E$, c1.1 | ![Chemical Structure](image) | $C_1$ | -1281.153988 (5.2) |
| | | C4a-C8a-S-C2 = 30.6 | |
| | | C8a-S-C2-C(H) = 146.9 | |
| | | S-C2-C(H)-C(H) = 169.6 | |
| | | C2-C(H)-C(H)-C(H) = 179.9 | |
| | | C(H)-C(H)-C(H)-C1' = -179.8 | |
| | | C(H)-C(H)-C1'-C2' = 0.4 | |
| | | C3'-C4'-N-C(H$_3$) = -0.6 | |
| | | C3'-C4'-N-C(H$_3$) = 179.6 | |
| $E$, $sp$, $E$, c1.1 | ![Chemical Structure](image) | $C_1$ | -1281.143801 (11.6) |
| | | C4a-C8a-S-C2 = 33.9 | |
| | | C8a-S-C2-C(H) = 142.1 | |
| | | S-C2-C(H)-C(H) = -167.2 | |
| | | C2-C(H)-C(H)-C(H) = 25.8 | |
| | | C(H)-C(H)-C(H)-C1' = -178.3 | |
| | | C(H)-C(H)-C1'-C2' = 9.4 | |
| | | C3'-C4'-N-C(H$_3$) = 0.0 | |
| | | C3'-C4'-N-C(H$_3$) = 179.9 | |
| Configuration | Bond Angles and Distances | Energy Difference |
|---------------|--------------------------|------------------|
| $E, sp, E, c1.2$ | ![Chemical Structure](image) | $C_2$<br>$\begin{align*}
    C4a-C8a-S-C2 &= 27.0 \\
    C8a-S-C2-C(H) &= 150.9 \\
    S-C2-C(H)-C(H) &= 140.2 \\
    C2-C(H)-C(H)-C(H) &= -18.7 \\
    C(H)-C(H)-C(H)-C1' &= 178.8 \\
    C(H)-C(H)-C1'-C2' &= -6.6 \\
    C3'-C4'-N-C(H_3) &= 0.4 \\
    C3'-C4'-N-C(H_3) &= -179.6 \\
\end{align*}$ | $-1281.144521 (11.2)$ | $-1280.829020 (12.1)$ |
| $Z, ap, E, c1.1$ | ![Chemical Structure](image) | $C_2$<br>$\begin{align*}
    C4a-C8a-S-C2 &= 23.6 \\
    C8a-S-C2-C(H) &= 157.0 \\
    S-C2-C(H)-C(H) &= -7.5 \\
    C2-C(H)-C(H)-C(H) &= 179.3 \\
    C(H)-C(H)-C(H)-C1' &= 179.3 \\
    C(H)-C(H)-C1'-C2' &= -0.5 \\
    C3'-C4'-N-C(H_3) &= 0.5 \\
    C3'-C4'-N-C(H_3) &= -179.8 \\
\end{align*}$ | $-1281.162338 (0.0)$ | $-1280.848332 (0.0)$ |
| Z, sp, E, c1.1 | $\begin{align*} C_2 \\
C4a-C8a-S-C2 &= 18.0 \\
C8a-S-C2-C(H) &= 162.2 \\
S-C2-C(H)-C(H) &= -3.5 \\
C2-C(H)-C(H)-C(H) &= 8.6 \\
C(H)-C(H)-C(H)-C1' &= -178.6 \\
C(H)-C(H)-C1'-C2' &= 3.7 \\
C3'-C4'-N-C(H_3) &= 0.1 \\
C3'-C4'-N-C(H_3) &= 179.9 \end{align*}$ | -1281.154731 (4.8) | -1280.840205 (5.1) |
| Z, sp, E, c1.2 | $\begin{align*} \text{approx. } C_2 \\
C4a-C8a-S-C2 &= 0.9 \\
C8a-S-C2-C(H) &= 179.2 \\
S-C2-C(H)-C(H) &= -0.2 \\
C2-C(H)-C(H)-C(H) &= 0.3 \\
C(H)-C(H)-C(H)-C1' &= -179.9 \\
C(H)-C(H)-C1'-C2' &= 0.0 \\
C3'-C4'-N-C(H_3) &= 0.0 \\
C3'-C4'-N-C(H_3) &= 180.0 \end{align*}$ | -1281.154565 (4.9) | saddle point |

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| $E, ap, Z, c1.1$ | $C_2$ | $-1281.145516 (10.6)$ | $-1280.830135 (11.4)$ |
| --- | --- | --- | --- |
| ![Molecule](image1.png) | C4a-C8a-S-C2 = 30.8  
C8a-S-C2-C(H) = 146.8  
S-C2-C(H)-C(H) = -178.8  
C2-C(H)-C(H)-C(H) = -174.7  
C(H)-C(H)-C(H)-C1' = 15.5  
C(H)-C(H)-C1'-C2' = 20.9  
C3'-C4'-N-C(H3) = -0.3  
C3'-C4'-N-C(H3) = 176.6 |  |  |

| $E, ap, Z, c1.2$ | $C_1$ | $-1281.145858 (10.3)$ | $-1280.830343 (11.3)$ |
| --- | --- | --- | --- |
| ![Molecule](image2.png) | C4a-C8a-S-C2 = 27.3  
C8a-S-C2-C(H) = 149.7  
S-C2-C(H)-C(H) = 156.5  
C2-C(H)-C(H)-C(H) = 172.6  
C(H)-C(H)-C(H)-C1' = -15.2  
C(H)-C(H)-C1'-C2' = -19.4  
C3'-C4'-N-C(H3) = 1.7  
C3'-C4'-N-C(H3) = -175.8 |  |  |
| $E, +sc, Z, c1.1$ | $C_1$ | $E, -sc, Z, c1.1$ | $C_1$ |
|------------------|-------|------------------|-------|
| ![Molecule](image) | C4a-C8a-S-C2 = 32.3 | C4a-C8a-S-C2 = 26.2 |
|                  | C8a-S-C2-C(H) = 144.4 | C8a-S-C2-C(H) = 147.7 |
|                  | S-C2-C(H)-C(H) = 178.1 | S-C2-C(H)-C(H) = 156.6 |
|                  | C2-C(H)-C(H)-C(H) = 40.1 | C2-C(H)-C(H)-C(H) = -35.3 |
|                  | C(H)-C(H)-C(H)-C1' = 9.5 | C(H)-C(H)-C(H)-C1' = -12.6 |
|                  | C(H)-C(H)-C1'-C2' = 13.2 | C(H)-C(H)-C1'-C2' = -9.2 |
|                  | C3'-C4'-N-C(H$_3$) = 1.5 | C3'-C4'-N-C(H$_3$) = -0.9 |
|                  | C3'-C4'-N-C(H$_3$) = 179.2 | C3'-C4'-N-C(H$_3$) = -179.3 |
|                  | $-1281.133644 (18.0)$ | $-1281.134694 (17.3)$ |
|                  | $-1280.818440 (18.8)$ | $-1280.819379 (18.2)$ |
| Z, ap, Z, c1.1 | C_2  | -1281.154384 (5.0) | -1280.839621 (5.5) |
|----------------|------|-------------------|-------------------|
| ![Chemical Structure](image1) | C4a-C8a-S-C2 = 20.7 | C8a-S-C2-C(H) = 161.0 |
| | S-C2-C(H)-C(H) = -11.8 | C2-C(H)-C(H)-C(H) = 174.9 |
| | C(H)-C(H)-C(H)-C1' = -15.1 | C(H)-C(H)-C1’-C2’ = -19.0 |
| | C3’-C4’-N-C(H_3) = 0.3 | C3’-C4’-N-C(H_3) = -176.7 |
| Z, ap, Z, c1.2 | C_2  | -1281.153518 (5.5) | -1280.839131 (5.8) |
| ![Chemical Structure](image2) | C4a-C8a-S-C2 = 14.2 | C8a-S-C2-C(H) = 166.7 |
| | S-C2-C(H)-C(H) = 1.2 | C2-C(H)-C(H)-C(H) = -177.1 |
| | C(H)-C(H)-C(H)-C1' = 13.3 | C(H)-C(H)-C1’-C2’ = 20.7 |
| | C3’-C4’-N-C(H_3) = 0.2 | C3’-C4’-N-C(H_3) = 177.2 |
| Z, +sc, Z, c1.1 | ![Molecular Structure](image) | $C_2$ | -1281.144947 (10.9) | -1280.829321 (11.9) |
|---|---|---|---|---|
| | | C4a-C8a-S-C2 = 12.0 | | |
| | | C8a-S-C2-C(H) = 164.7 | | |
| | | S-C2-C(H)-C(H) = -1.4 | | |
| | | C2-C(H)-C(H)-C(H) = 34.0 | | |
| | | C(H)-C(H)-C(H)-C1' = 22.3 | | |
| | | C(H)-C(H)-C1’-C2’ = 13.6 | | |
| | | C3’-C4’-N-C(H$_3$) = 0.3 | | |
| | | C3’-C4’-N-C(H$_3$) = 177.5 | | |
| Diprotonated form in methanol | | | | |
| E, ap, E, c1.1 | ![Molecular Structure](image) | $C_2$ | -1281.581022 (5.3) | -1281.248344 (6.3) |
| | | C4a-C8a-S-C2 = 27.7 | | |
| | | C8a-S-C2-C(H) = 145.6 | | |
| | | S-C2-C(H)-C(H) = 171.7 | | |
| | | C2-C(H)-C(H)-C(H) = -179.7 | | |
| | | C(H)-C(H)-C(H)-C1’ = -179.6 | | |
| | | C(H)-C(H)-C1’-C2’ = 0.3 | | |
| | | C3’-C4’-N-C(H$_3$) = 114.5 | | |
| | | C3’-C4’-N-C(H$_3$) = -118.0 | | |
| $E, +sc, E, c1.1$ | $C_{1}$ | $-1281.572398 (10.7)$ | $-1281.239690 (11.7)$ |
|---|---|---|---|
| ![Chemical Structure 1](image1.png) | C4a-C8a-S-C2 = 31.4  
C8a-S-C2-C(H) = 135.9  
S-C2-C(H)-C(H) = -175.8  
C2-C(H)-C(H)-C(H) = 37.0  
C(H)-C(H)-C(H)-C1' = 178.1  
C(H)-C(H)-C1'-C2' = 12.4  
C3'-C4'-N-C(H$_3$) = 118.0  
C3'-C4'-N-C(H$_3$) = -114.6 | | |

| $E, -sc, E, c1.1$ | $C_{1}$ | $-1281.570051 (12.2)$ | $-1281.239026 (12.1)$ |
|---|---|---|---|
| ![Chemical Structure 2](image2.png) | C4a-C8a-S-C2 = 22.8  
C8a-S-C2-C(H) = 149.7  
S-C2-C(H)-C(H) = 153.2  
C2-C(H)-C(H)-C(H) = -39.3  
C(H)-C(H)-C(H)-C1' = -176.1  
C(H)-C(H)-C1'-C2' = -10.4  
C3'-C4'-N-C(H$_3$) = 117.6  
C3'-C4'-N-C(H$_3$) = -115.0 | | |
| Z, ap, E, c1.1 | $C_2$ | -1281.589510 (0.0) | -1281.258353 (0.0) |
|---|---|---|---|
| ![Structure](image1) | C4a-C8a-S-C2 = 20.9 | C8a-S-C2-C(H) = 158.1 | S-C2-C(H)-C(H) = -8.5 |
|  | C2-C(H)-C(H)-C(H) = 176.8 | C(H)-C(H)-C(H)-C1’ = 179.8 | C(H)-C(H)-C1’-C2’ = -2.0 |
|  | C3’-C4’-N-(H) = 115.3 | C3’-C4’-N-(H) = -117.4 | |

| Z, ap, E, c1.2 | $C_1$ | -1281.589493 (0.0) | -1281.258127 (0.1) |
|---|---|---|---|
| ![Structure](image2) | C4a-C8a-S-C2 = 21.3 | C8a-S-C2-C(H) = 157.2 | S-C2-C(H)-C(H) = -8.7 |
|  | C2-C(H)-C(H)-C(H) = 177.9 | C(H)-C(H)-C(H)-C1’ = 178.9 | C(H)-C(H)-C1’-C2’ = 2.6 |
|  | C3’-C4’-N-(H) = 119.6 | C3’-C4’-N-(H) = -113.0 | |
| Z, sp, E, c1.1 | $C_2$ | -1281.582944 (4.1) | -1281.252205 (3.9) |
|----------------|--------|------------------|------------------|
| ![Chemical Structure](attachment:image1.png) | C4a-C8a-S-C2 = 13.9  
C8a-S-C2-C(H) = 164.4  
S-C2-C(H)-C(H) = -3.9  
C2-C(H)-C(H)-C(H) = 14.5  
C(H)-C(H)-C(H)-C1' = -179.7  
C(H)-C(H)-C1'-C2' = 7.8  
C3'-C4'-N-C(H3) = 112.7  
C3'-C4'-N-C(H3) = -119.9 | ![Chemical Structure](attachment:image2.png) | $C_1$ | -1281.582878 (4.2) | -1281.250650 (4.8) |
| ![Chemical Structure](attachment:image3.png) | C4a-C8a-S-C2 = 19.2  
C8a-S-C2-C(H) = 156.2  
S-C2-C(H)-C(H) = -5.7  
C2-C(H)-C(H)-C(H) = 23.6  
C(H)-C(H)-C(H)-C1' = -177.9  
C(H)-C(H)-C1'-C2' = 17.0  
C3'-C4'-N-C(H3) = 116.2  
C3'-C4'-N-C(H3) = -116.3 |
| $Z$, $sp$, $E$, c1.3 | $C_1$ | $C_2$- $C_8a-S-C2 = 7.8$ | $C_8a-S-C2-C(H) = 171.9$ |
|----------------------|-------|-------------------------|---------------------------|
|                      |       | S-C2-C(H)-C(H) = -2.6    | $C_2-C(H)-C(H)-C(H) = 6.0$ | $C(H)-C(H)-C(H)-C1' = -179.6$ |
|                      |       | $C(H)-C(H)-C1'-C2' = -0.9$ |                           |
|                      |       | $C3'-C4'^-N-C(H_3) = 116.5$ |                           |
|                      |       | $C3'-C4'^-N-C(H_3) = -116.0$ |                           |
| $E$, $ap$, $Z$, c1.1 | $C_1$ | $C4a-C8a-S-C2 = 28.2$    | $C8a-S-C2-C(H) = 145.0$  |
|                      |       | $S-C2-C(H)-C(H) = 178.2$ |                           |
|                      |       | $C2-C(H)-C(H)-C(H) = -171.3$ |                           |
|                      |       | $C(H)-C(H)-C(H)-C1' = 9.3$ |                           |
|                      |       | $C(H)-C(H)-C1'-C2' = 34.7$ |                           |
|                      |       | $C3'-C4'^-N-C(H_3) = 114.4$ |                           |
|                      |       | $C3'-C4'^-N-C(H_3) = -118.0$ |                           |
### $E, ap, Z, c1.2$

| Bond Lengths and Angles | $C_2$ | $E$-Energy | $E$-Energy SD |
|------------------------|-------|------------|---------------|
| C4a-C8a-S-C2           | 25.8  | -1281.574607 (9.4) |               |
| C8a-S-C2-C(H)          | 146.8 | -1281.243037 (9.6) |               |
| S-C2-C(H)-C(H)         | 164.1 | -1281.565028 (15.4) |               |
| C2-C(H)-C(H)-C(H)      | 169.9 | -1281.234172 (15.2) |               |
| C(H)-C(H)-C1'-C1'     | -7.9  | -1281.574607 (9.4) |               |
| C(H)-C(H)-C1'-C2'     | -34.8 | -1281.243037 (9.6) |               |
| C3'-C4'-N-C(H3)       | 115.3 | -1281.565028 (15.4) |               |
| C3'-C4'-N-C(H3)       | -117.2 | -1281.234172 (15.2) |               |

### $E, +sc, Z, c1.1$

| Bond Lengths and Angles | $C_2$ | $E$-Energy | $E$-Energy SD |
|------------------------|-------|------------|---------------|
| C4a-C8a-S-C2           | 29.9  | -1281.574607 (9.4) |               |
| C8a-S-C2-C(H)          | 138.1 | -1281.243037 (9.6) |               |
| S-C2-C(H)-C(H)         | 176.1 | -1281.565028 (15.4) |               |
| C2-C(H)-C(H)-C(H)      | 57.9  | -1281.234172 (15.2) |               |
| C(H)-C(H)-C1'-C1'     | 2.3   | -1281.574607 (9.4) |               |
| C(H)-C(H)-C1'-C2'     | 34.3  | -1281.243037 (9.6) |               |
| C3'-C4'-N-C(H3)       | 114.2 | -1281.565028 (15.4) |               |
| C3'-C4'-N-C(H3)       | -118.3 | -1281.234172 (15.2) |               |
$E, \cdot -sc, Z, c1.1$

\[
\begin{array}{c}
\text{C}_2 \\
\text{C4a-C8a-S-C2} = 26.6 \\
\text{C8a-S-C2-C(H)} = 142.0 \\
\text{S-C2-C(H)-C(H)} = 169.4 \\
\text{C2-C(H)-C(H)-C(H)} = -69.4 \\
\text{C(H)-C(H)-C(H)-C1} = 0.1 \\
\text{C(H)-C(H)-C1'-C2'} = 28.1 \\
\text{C3'-C4'-N-C(H3)} = 116.0 \\
\text{C3'-C4'-N-C(H3)} = -116.6 \\
\end{array}
\]

-1281.564582 (15.6) -1281.233168 (15.8)

$Z, ap, Z, c1.1$

\[
\begin{array}{c}
\text{C}_2 \\
\text{C4a-C8a-S-C2} = 19.4 \\
\text{C8a-S-C2-C(H)} = 160.3 \\
\text{S-C2-C(H)-C(H)} = -11.8 \\
\text{C2-C(H)-C(H)-C(H)} = 169.6 \\
\text{C(H)-C(H)-C(H)-C1} = -9.3 \\
\text{C(H)-C(H)-C1'-C2'} = -31.9 \\
\text{C3'-C4'-N-C(H3)} = 121.4 \\
\text{C3'-C4'-N-C(H3)} = -111.0 \\
\end{array}
\]

-1281.583517 (3.8) -1281.252503 (3.7)
| Isomer / conformer | Schematic drawing | $\lambda$ / nm ($f$): orbitalic contribution (expansion coefficient)$^a$ |
|--------------------|-------------------|---------------------------------------------------------------|
| Neutral form in methanol | ![Schematic](image) | -1281.575670 (8.7) | -1281.243505 (9.3) |
|                      |                   | ![Molecule](image)                                             |                                 |

Table 3.2. 3-Methylbenzothiazine: electronic transitions [TD-PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)] for the most stable structures identified, and isodensity maps (0.04 a.u.) of selected molecular orbitals
$Z, ap, E, c1.1$

499.2 (1.06): 85 → 86 (0.70)
362.9 (0.14): 84 → 86 (0.69)
355.6 (0.45): 84 → 87 (0.12); 85 → 87 (0.68)
319.1 (0.01): 83 → 86 (-0.31); 84 → 88 (0.14); 85 → 88 (0.59); 85 → 89 (0.11)
311.0 (0.12): 81 → 86 (-0.17); 83 → 86 (0.14); 85 → 89 (0.64)
305.3 (0.04): 80 → 86 (0.46); 80 → 87 (-0.12); 82 → 86 (0.17); 83 → 86 (-0.36); 85 → 88 (-0.28); 85 → 89 (0.13)

#81, HOMO-4 (-0.27485)
#82, HOMO-3 (-0.27427)
#83, HOMO-2 (-0.26001)
#84, HOMO-1 (-0.22716)
#85, HOMO (-0.19003)
| # & LUMO & LUMO+1 & LUMO+2 & LUMO+3 & LUMO+4 & (isodensity level 0.016 a.u.) |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| #86, LUMO (-0.08073)            | #87, LUMO+1 (-0.03511)          | #88, LUMO+2 (-0.02076)          | #89, LUMO+3 (-0.01417)          | #90, LUMO+4 (-0.00265)          |                                  |

**Monoprotonated (iminium) form in methanol**

**$Z, \text{ap}, E, c1.1$**

| & 605.7 (1.09): 84 → 86 (-0.13); 85 → 86 (0.69) | 427.1 (0.40): 83 → 86 (0.10); 84 → 86 (0.68); 85 → 86 (0.13) | 358.3 (0.34): 84 → 87 (-0.14); 85 → 87 (0.68) | 333.0 (0.06): 83 → 86 (0.64); 85 → 88 (0.24) | 321.7 (0.00): 82 → 86 (0.68); 85 → 89 (-0.16) | 308.5 (0.13): 83 → 86 (-0.24); 84 → 87 (0.12); 84 → 88 (-0.12); 85 → 88 (0.63) |

---

## Image 1

[Image of molecular structures]

---

$\text{SN+Me}_2\text{Me}$

$\text{Me}_2\text{Me}$

$\text{Me}_2\text{Me}$

$\text{Me}_2\text{Me}$
| #   | HOMO   | Energy   | #   | HOMO   | Energy   | #   | HOMO   | Energy   | #   | HOMO   | Energy   |
|-----|--------|----------|-----|--------|----------|-----|--------|----------|-----|--------|----------|
| #81 | HOMO-4 | -0.29562 | #82 | HOMO-3 | -0.28958 | #83 | HOMO-2 | -0.28126 | #84 | HOMO-1 | -0.24479 |
| #85 | HOMO   | -0.20879 | #86 | LUMO   | -0.11957 | #87 | LUMO+1 | -0.05396 | #88 | LUMO+2 | -0.03642 |
| #89 | LUMO+3 | -0.02555 | #90 | LUMO+4 | -0.01467 |

Diprotonated form in methanol
$Z, ap, E, c\, 1.1$

\[
\begin{align*}
551.0 (0.53) &: \quad 85 \rightarrow 86 (0.70) \\
367.0 (0.31) &: \quad 84 \rightarrow 86 (0.66); \quad 85 \rightarrow 87 (0.21) \\
342.2 (0.61) &: \quad 83 \rightarrow 86 (-0.15); \quad 84 \rightarrow 86 (-0.18); \quad 85 \rightarrow 86 (-0.10); \quad 85 \rightarrow 87 (0.65) \\
323.1 (0.25) &: \quad 83 \rightarrow 86 (0.67); \quad 84 \rightarrow 86 (-0.12); \quad 85 \rightarrow 87 (0.10); \quad 85 \rightarrow 89 (0.11) \\
309.4 (0.01) &: \quad 82 \rightarrow 86 (0.67); \quad 85 \rightarrow 88 (0.18)
\end{align*}
\]

#81, HOMO-4 (-0.32863) #82, HOMO-3 (-0.30785) #83, HOMO-2 (-0.29794) #84, HOMO-1 (-0.28598) #85, HOMO (-0.23839)
Figure 3.1. 3-Methylbenzothiazine: plot of selected orbital energies [PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)]

[a] Only transitions above 300 nm are reported. Transitions with \( f > 0.1 \) and their main contributions are highlighted.

[b] Orbital energies in hartrees.
Figure 3.2. 3-Methylbenzothiazine: TD-PBE0 calculations
Figure 3.3. 3-Methylbenzothiazine: TD-M06-2X calculations
### Table 3.3. 3-Phenylbenzothiazine: conformational exploration

| Isomer / conformer | Schematic drawing | Symmetry | $E$ or $G_{PCM}$ / hartree | $G_{RRHO}$ or $G_{PCM,RRHO}$ / hartree |
|--------------------|-------------------|----------|-----------------------------|--------------------------------------|
|                    |                   |          | ($\Delta E$ or $\Delta G_{PCM}$ / kcal mol$^{-1}$) | ($\Delta G_{RRHO}$ or $\Delta G_{PCM,RRHO}$ / kcal mol$^{-1}$) |
| Neutral form in vacuo |                   |          |                             |                                      |
| $E, ap, E, c1.1$ | ![Chemical Structure] | $C_2$ | $-1472.215227 (2.5)$ | $-1471.865781 (2.9)$ |
|-----------------|-----------------------|-------|------------------------|------------------------|
|                 |                       | C4a-C8a-S-C2 = 26.4 |                       |                        |
|                 |                       | C8a-S-C2-C(H) = 131.0 |                       |                        |
|                 |                       | S-C2-C(H)-C(H) = 178.9 |                       |                        |
|                 |                       | C2-C3-C1''-C2'' = 28.0 |                       |                        |
|                 |                       | C2-C(H)-C(H)-C(H) = -179.1 |                       |                        |
|                 |                       | C(H)-C(H)-C(H)-C1' = -179.4 |                       |                        |
|                 |                       | C(H)-C(H)-C1'-C2' = -2.1 |                       |                        |
|                 |                       | C3'-C4'-N-C(H$_3$) = 7.8 |                       |                        |
|                 |                       | C3'-C4'-N-C(H$_3$) = 173.4 |                       |                        |

| $E, sp, E, c1.1$ | ![Chemical Structure] | $C_2$ | $-1472.206750 (7.8)$ | $-1471.857743 (7.9)$ |
|-----------------|-----------------------|-------|------------------------|------------------------|
|                 |                       | C4a-C8a-S-C2 = 27.8 |                       |                        |
|                 |                       | C8a-S-C2-C(H) = 127.8 |                       |                        |
|                 |                       | S-C2-C(H)-C(H) = -177.6 |                       |                        |
|                 |                       | C2-C3-C1''-C2'' = 20.3 |                       |                        |
|                 |                       | C2-C(H)-C(H)-C(H) = 26.9 |                       |                        |
|                 |                       | C(H)-C(H)-C(H)-C1' = 178.7 |                       |                        |
|                 |                       | C(H)-C(H)-C1'-C2' = 7.9 |                       |                        |
|                 |                       | C3'-C4'-N-C(H$_3$) = 8.0 |                       |                        |
| Configuration | Bond Lengths | Energy (kcal/mol) |
|---------------|-------------|------------------|
| Z, op, E, c1.1 | C3'-C4'-N-C(H) = 172.4 | -1472.219162 (0.0) |
|               | C2          | -1471.881861 (0.0) |
|               | C4a-C8a-S-C2 = 22.9 |               |
|               | C8a-S-C2-C(H) = 143.2 |               |
|               | S-C2-C(H)-C(H) = -6.7 |               |
|               | C2-C3-C1'-C2'' = 38.7 |               |
|               | C2-C(H)-C(H)-C(H) = 177.4 |               |
|               | C(H)-C(H)-C(H)-C1' = 178.2 |               |
|               | C(H)-C(H)-C1'-C2' = -1.5 |               |
|               | C3'-C4'-N-C(H) = 7.3 |               |
|               | C3'-C4'-N-C(H) = 173.2 |               |
| Z, op, E, c1.2 | C2          | -1472.219176 (0.0) |
|               | C4a-C8a-S-C2 = 23.0 | -1471.870191 (0.1) |
|               | C8a-S-C2-C(H) = 143.1 |               |
|               | S-C2-C(H)-C(H) = -6.7 |               |
|               | C2-C3-C1'-C2'' = 38.7 |               |
|               | C2-C(H)-C(H)-C(H) = 177.6 |               |
|               | C(H)-C(H)-C(H)-C1' = 178.1 |               |
|               | C(H)-C(H)-C1'-C2' = -2.1 |               |
| Z, sp, E, c1.1 | C2  | C2  |
|----------------|-----|-----|
|                | C4a-C8a-S-C2 = 19.5 | -1472.212852 (4.0) |
|                | C8a-S-C2-(H) = 146.3 | -1471.863460 (4.3) |
|                | S-C2-(H)-(H) = -2.7  |               |
|                | C2-C3-C1"-C2" = 39.7 |               |
|                | C2-(H)-(H)-(H) = 23.8|               |
|                | C(H)-(H)-(H)-C1' = -178.1|           |
|                | C(H)-(H)-C1'-C2' = 11.7|           |
|                | C3'-C4'-(H)-(H) = 8.7 |               |
|                | C3'-C4'-(H)-(H) = 171.6|           |

| Z, sp, E, c1.2 | C2  | C2  |
|----------------|-----|-----|
|                | C4a-C8a-S-C2 = 19.5 | -1472.212810 (4.0) |
|                | C8a-S-C2-(H) = 146.4 | -1471.863621 (4.2) |
|                | S-C2-(H)-(H) = -2.6  |               |
|                | C2-C3-C1"-C2" = 39.7 |               |
|                | C2-(H)-(H)-(H) = 23.7|               |
|                | C(H)-(H)-(H)-C1' = -178.1|          |
| E, ap, Z, c1.1 | C(H)\text{-}C(H)\text{-}C1\text{'}\text{-}C2\text{'} = 10.2 |
|----------------|--------------------------------------------------|
|                 | C3\text{'}\text{-}C4\text{'}\text{-}N\text{-}C(H_3) = -8.6 |
|                 | C3\text{'}\text{-}C4\text{'}\text{-}N\text{-}C(H_3) = -172.7 |

| E, ap, Z, c1.1 | C_2 |
|----------------|-----|
|                 | C4a-C8a-S-C2 = 25.9 |
|                 | C8a-S-C2-C(H) = 131.7 |
|                 | S-C2-C(H)_2-C(H) = -177.9 |
|                 | C2-C3-C1\text{'}\text{-}C2\text{''} = 26.6 |
|                 | C2-C(H)_2-C(H)\text{-}C(H) = -172.3 |
|                 | C(H)_2-C(H)_2-C1\text{'} = 8.7 |
|                 | C(H)_2-C1\text{'}\text{-}C2\text{'} = 30.3 |
|                 | C3\text{'}\text{-}C4\text{'}\text{-}N\text{-}C(H_3) = 7.9 |
|                 | C3\text{'}\text{-}C4\text{'}\text{-}N\text{-}C(H_3) = 170.4 |

| E, ap, Z, c1.2 | C_2 |
|----------------|-----|
|                 | C4a-C8a-S-C2 = 26.0 |
|                 | C8a-S-C2-C(H) = 129.6 |
|                 | S-C2-C(H)_2-C(H) = 176.5 |
|                 | C2-C3-C1\text{'}\text{-}C2\text{''} = 28.7 |
|                 | C2-C(H)_2-C(H)\text{-}C(H) = 172.0 |

|-1472.209685 (6.0) |
| -1471.859664 (6.7) |

-1472.208830 (6.5) |
| -1471.860471 (6.2) |
|          | Bond Lengths (Å) | Energy (kcal/mol) |
|----------|-----------------|-------------------|
|          | C(H)-C(H)-C(H)-C1' = 6.3 | -1472.200394 (11.8) |
|          | C(H)-C(H)-C1'-C2' = 32.7 | -1471.851429 (11.9) |
|          | C3'-C4'-N-C(H3) = 6.5 | -1472.200289 (11.9) |
|          | C3'-C4'-N-C(H3) = 175.3 | -1471.850653 (12.4) |

*E, +sc, Z, cl.1*
| Z, ap, Z, c1.1 | \[
\begin{align*}
\text{C2-C(H)-C(H)-C(H)} &= 52.3 \\
\text{C(H)-C(H)-C(H)-C1'} &= 4.6 \\ 
\text{C(H)-C(H)-C1'-C2'} &= 20.3 \\
\text{C3'-C4'-N-C(H3)} &= -8.9 \\
\text{C3'-C4'-N-C(H3)} &= -171.8 \\
\end{align*}
\] |
| C2 |
| C4a-C8a-S-C2 = 22.1 |
| C8a-S-C2-C(H) = 144.2 |
| S-C2-C(H)-C(H) = -3.0 |
| C2-C3-C1''-C2'' = 38.1 |
| C2-C(H)-C(H)-C(H) = -176.9 |
| C(H)-C(H)-C(H)-C1' = 5.7 |
| C(H)-C(H)-C1'-C2' = 30.5 |
| C3'-C4'-N-C(H3) = 7.8 |
| C3'-C4'-N-C(H3) = 169.8 |
| -1472.213173 (3.8) |
| -1471.863604 (4.2) |

| Z, ap, Z, c1.2 | \[
\begin{align*}
\text{C2-C(H)-C(H)-C(H)} &= 52.3 \\
\text{C(H)-C(H)-C(H)-C1'} &= 4.6 \\ 
\text{C(H)-C(H)-C1'-C2'} &= 20.3 \\
\text{C3'-C4'-N-C(H3)} &= -8.9 \\
\text{C3'-C4'-N-C(H3)} &= -171.8 \\
\end{align*}
\] |
| C2 |
| C4a-C8a-S-C2 = 22.1 |
| C8a-S-C2-C(H) = 143.4 |
| S-C2-C(H)-C(H) = -9.6 |
| -1472.214375 (3.0) |
| -1471.864272 (3.8) |
|                  | C2-C3-C1"-C2" = 39.7 |
|------------------|----------------------|
|                  | C2-C(H)-C(H)-C(H) = 173.0 |
|                  | C(H)-C(H)-C(H)-C1" = -8.1 |
|                  | C(H)-C(H)-C1"-C2" = -25.9 |
|                  | C3'-C4'-N-C(H3) = -8.5 |
|                  | C3'-C4'-N-C(H3) = -170.8 |

Z, ap, Z, c1.3

\[ Z, ap, Z, c1.3 \]

\[
\begin{align*}
C_2 & = -1472.214260 (3.1) \\
C_4a-S-2C & = 22.0 \\
C_8a-S-2C-C(H) & = 143.6 \\
N-C(H3) & = 7.2 \\
C_3'-C4'-N-C(H3) & = 175.7 \\
\end{align*}
\]
| Z, +sc, Z, c1.1 | $C_2$ | -1472.205669 (8.5) | -1471.855187 (9.5) |
|-----------------|--------|-------------------|-------------------|
| $C_2$ | C4a-C8a-S-C2 = 18.6 | **Z, +sc, Z, c1.2** | $C_2$ | -1472.205575 (8.5) | -1471.855647 (9.2) |
| | C8a-S-C2-C(H) = 147.2 | | $C_2$ | C4a-C8a-S-C2 = 18.5 | | C8a-S-C2-C(H) = 147.4 |
| | S-C2-C(H)-C(H) = -5.9 | | C2-C3-C1''-C2'' = 39.5 | | S-C2-C(H)-C(H) = -6.0 |
| | C2-C(H)-C(H)-C1'' = 12.4 | | C2-C(H)-C(H)-C1'' = 18.1 | | C2-C(H)-C(H)-C1'' = 12.5 |
| | C(H)-C(H)-C1''-C2'' = 18.1 | | C(H)-C(H)-C1''-C2'' = 18.0 | | C(H)-C(H)-C1''-C2'' = 18.0 |
| | C3'-C4''-N-C(H$_3$) = 9.0 | | C3'-C4''-N-C(H$_3$) = -9.1 | | C3'-C4''-N-C(H$_3$) = -9.1 |
| | C3'-C4''-N-C(H$_3$) = 170.4 | | | | |
| Structure | Bond Lengths | Energy (kcal/mol) | Geometry (°) |
|-----------|-------------|------------------|-------------|
| Z, -sc, Z, c1.1 | C=C1=C4a=C8a-S-C2 = 19.5 | -1472.203932 (9.6) | -1471.85316 (10.6) |
| Z, -sc, Z, c1.2 | C=C1=C4a-C8a-S-C2 = 19.3 | -1472.203752 (9.7) | -1471.854857 (9.7) |
| E, ap, E, c1.1 | C₂ | -1472.228451 (2.7) | -1471.879886 (2.9) |
|----------------|-----------------|-------------------|-------------------|
| ![Chemical Structure](image) | C₄a-C₈a-S-C₂ = 27.5 | C₈a-S-C₂-C(H) = 130.8 | S-C₂-C(H)-C(H) = 179.1 |
|                | C₂-C₃-C₁''-C₂'' = 31.3 | C₂-C(H)-C(H)-C(H) = -178.9 | C(H)-C(H)-C(H)-C₁'' = -179.3 |
|                | C₃''-C₄''-N-C(H) = 1.7 | C₃''-C₄''-N-C(H) = 178.7 | C(H)-C(H)-C₁''-C₂'' = -0.2 |

| E, sp, E, c1.1 | C₂ | -1472.220401 (7.8) | -1471.872238 (7.7) |
|----------------|-----------------|-------------------|-------------------|
| ![Chemical Structure](image) | C₄a-C₈a-S-C₂ = 29.1 | C₈a-S-C₂-C(H) = 128.3 | S-C₂-C(H)-C(H) = -176.5 |
|                | C₂-C₃-C₁''-C₂'' = 25.9 | C₂-C(H)-C(H)-C(H) = 30.0 | |
| Structural Data | Chemical Data |
|-----------------|---------------|
| Z, ap, E, c1.1  | C₂             |
|                 | C₄a-C₈a-S-C₂ = 24.0 |
|                 | C₈a-S-C₂-C(H) = 143.3 |
|                 | S-C₂-C(H)-C(H) = -6.4 |
|                 | C₂-C₃-C₁₁''-C₂'' = 41.4 |
|                 | C₂-C(H)-C(H)-C(H) = 178.6 |
|                 | C(H)-C(H)-C(H)-C₁ = 178.4 |
|                 | C(H)-C(H)-C₁-C₂ = -0.6 |
|                 | C₃'-C₄'-N-C(H₃) = -0.2 |
|                 | C₃'-C₄'-N-C(H₃) = -179.6 |
|                 | -1472.232757 (0.0) |
|                 | -1471.884488 (0.0) |
| Z, sp, E, c1.1 | \begin{align*} \text{C}_2 \\
\text{C4a-C8a-S-C2} &= 20.6 \\
\text{C8a-S-C2-C(H)} &= 146.1 \\
\text{S-C2-C(H)-C(H)} &= -2.6 \\
\text{C2-C3-C1''-C2''} &= 42.4 \\
\text{C2-C(H)-C(H)-C(H)} &= 23.9 \\
\text{C(H)-C(H)-C(H)-C1'} &= -178.3 \\
\text{C(H)-C(H)-C1'-C2'} &= 9.2 \\
\text{C3'-C4'-N-C(H)} &= 3.0 \\
\text{C3'-C4'-N-C(H)} &= 176.7 \\
\end{align*} | -1472.226343 (4.0) | -1471.878404 (3.8) |

| E, ap, Z, c1.1 | \begin{align*} \text{C}_2 \\
\text{C4a-C8a-S-C2} &= 26.9 \\
\text{C8a-S-C2-C(H)} &= 131.8 \\
\text{S-C2-C(H)-C(H)} &= -177.4 \\
\text{C2-C3-C1''-C2''} &= 29.7 \\
\text{C2-C(H)-C(H)-C(H)} &= -171.9 \\
\text{C(H)-C(H)-C(H)-C1'} &= 9.3 \\
\text{C(H)-C(H)-C1'-C2'} &= 27.5 \\
\text{C3'-C4'-N-C(H)} &= 6.1 \\
\end{align*} | -1472.222305 (6.6) | -1471.872738 (7.4) |
| $E$, $ap$, $Z$, c1.2 | $C_2$ | $-1472.221376 (7.1)$ | $-1471.871829 (7.9)$ |
|---------------------|------|-----------------------|-----------------------|
| ![Diagram](image1)  | C4a-C8a-S-C2 = 26.9 | C8a-S-C2-C(H) = 129.7 |  |
|                     | S-C2-C(H)-C(H) = 176.1 | C2-C3-C1'-C2'' = 32.4 |  |
|                     | C2-C(H)-C(H)-C(H) = 172.5 | C2-C(H)-C(H)-C1' = -6.5 |  |
|                     | C(H)-C(H)-C1'-C2' = -29.2 | C3'-C4'-N-C(H) = -6.4 |  |
|                     | C3'-C4'-N-C(H) = -171.8 |  |  |

| $E$, +sc, $Z$, c1.1 | $C_2$ | $-1472.212999 (12.4)$ | $-1471.862889 (13.6)$ |
|---------------------|------|-----------------------|-----------------------|
| ![Diagram](image2)  | C4a-C8a-S-C2 = 27.6 | C8a-S-C2-C(H) = 131.4 |  |
|                     | S-C2-C(H)-C(H) = 176.4 | C2-C3-C1'-C2'' = 29.2 |  |
|                     | C2-C(H)-C(H)-C(H) = 54.0 | C(H)-C(H)-C(H)-C1' = 4.3 |  |
|                     | C(H)-C(H)-C1'-C2' = 17.3 |  |  |
| $E, +sc, Z, c1.2$ | $C_2$ |
|------------------|-------|
| C4a-C8a-S-C2 = 27.5 |
| C8a-S-C2-C(H) = 131.4 |
| S-C2-C(H)-C(H) = 176.2 |
| C2-C3-C1"-C2" = 29.3 |
| C2-C(H)-C(H)-C(H) = 53.7 |
| C(H)-C(H)-C1'-C2' = 4.6 |
| C(H)-C(H)-C1'-C2' = 17.6 |
| C3'-'C4'-N-C(H) = -4.3 |
| C3'-'C4'-N-C(H) = -176.4 |
| -1472.212878 (12.5) | saddle point |
| $Z, ap, Z, c1.1$ | $C_2$ |
| C4a-C8a-S-C2 = 22.6 |
| C8a-S-C2-C(H) = 144.9 |
| S-C2-C(H)-C(H) = -2.5 |
| C2-C3-C1"-C2" = 42.0 |
| C2-C(H)-C(H)-C(H) = -176.2 |
| C(H)-C(H)-C(H)-C1' = 6.1 |
| -1472.225989 (4.2) | -1471.876843 (4.8) |
Z, ap, Z, c1.2

|  | C(H)-C(H)-C1’-C2’ = 26.8 |
|---|---------------------------|
|  | C3’-C4’-N-C(H3) = 5.8 |
|  | C3’-C4’-N-C(H3) = 172.2 |

-1472.227191 (3.5)  -1471.877802 (4.2)

Z, +sc, Z, c1.1

|  | C(H)-C(H)-C1’-C2’ = 42.6 |
|---|---------------------------|
|  | C3’-C4’-N-C(H3) = 6.6 |
|  | C3’-C4’-N-C(H3) = 172.7 |

-1472.218911 (8.7)  -1471.868573 (10.0)
Z, +sc, Z, c1.2

| Bond Lengths | Equation 1 | Equation 2 |
|--------------|------------|------------|
| C(H)-C(H)-C(H)-C1' | 12.7       | -1472.218911 (8.7) saddle point |
| C(H)-C(H)-C1'-C2' | 17.7       |           |
| C3'-C4'-N-C(H3)  | 7.8        |           |
| C3'-C4'-N-C(H3)  | 172.0      |           |

Z, +sc, Z, c1.2

![Chemical Structure]
| Z, -sc, Z, c1.1 | $C_2$ | -1472.216465 (10.2) | -1471.866338 (11.4) |
|----------------|-------|---------------------|---------------------|
| \[\begin{align*}
C4a-C8a-S-C2 &= 18.9 \\
C8a-S-C2-C(H) &= 151.6 \\
S-C2-C(H)-C(H) &= -4.0 \\
C2-C3-C1''-C2'' &= 47.1 \\
C2-C(H)-C(H)-C(H) &= -47.7 \\
C(H)-C(H)-C(H)-C1' &= -6.3 \\
C(H)-C(H)-C1'-C2' &= -14.2 \\
C3'-C4'-N-C(H_3) &= -7.2 \\
C3'-C4'-N-C(H_3) &= -172.2 \\
\end{align*}\]| |
| Monoprotonated (iminium) form in methanol |

| $E, ap, E, c1.1$ | $C_2$ | -1472.677451 (5.4) | -1472.314065 (5.1) |
|----------------|-------|---------------------|---------------------|
| \[\begin{align*}
C4a-C8a-S-C2 &= 33.7 \\
C8a-S-C2-C(H) &= 135.3 \\
S-C2-C(H)-C(H) &= 179.8 \\
C2-C3-C1''-C2'' &= 48.0 \\
C2-C(H)-C(H)-C(H) &= 178.9 \\
C(H)-C(H)-C(H)-C1' &= -179.1 \\
C(H)-C(H)-C1'-C2' &= -1.3 \\
\end{align*}\]| |

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|                | C3'-C4'-N-C(H₃) = 0.0           | C3'-C4'-N-C(H₃) = 179.7 |
|----------------|--------------------------------|-------------------------|
| **E, sp, E, c1.1** | ![Image](image1.png) | ![Image](image2.png) |
| C₂              | -1472.667373 (11.7)            | -1472.303384 (11.8)    |
| C4a-C8a-S-C2    | 35.6                          |                         |
| C8a-S-C2-C(H)   | 134.4                         |                         |
| S-C2-C(H)-C(H)  | -167.4                        |                         |
| C2-C3-C1''-C2'' | 37.7                          |                         |
| C2-C(H)-C(H)-C(H) | 25.3                   |                         |
| C(H)-C(H)-C(H)-C1' | -177.8                 |                         |
| C(H)-C(H)-C1'-C2' | 9.4                     |                         |
| C3'-C4'-N-C(H₃) | 0.0                           |                         |
| C3'-C4'-N-C(H₃) | 179.6                         |                         |
| **E, sp, E, c1.2** | ![Image](image1.png) | ![Image](image2.png) |
| C₂              | -1472.664355 (13.6)            | -1472.301053 (13.3)    |
| C4a-C8a-S-C2    | 26.4                          |                         |
| C8a-S-C2-C(H)   | 154.8                         |                         |
| S-C2-C(H)-C(H)  | 137.6                         |                         |
| C2-C3-C1''-C2'' | -56.2                         |                         |
| C2-C(H)-C(H)-C(H) | -15.8                  |                         |
| C(H)-C(H)-C(H)-C1' | 176.4                 |                         |
| $Z$, $ap$, $E$, c1.1 | | | |
|---|---|---|---|
| ![Molecular Structure](image) | C(H)-C(H)-C1'-C2' = -7.1 |
| | C3'-C4'-N-C(H$_3$) = -0.3 |
| | C3'-C4'-N-C(H$_3$) = 179.8 |
| C$_2$ | -1472.686044 (0.0) |
| C4a-C8a-S-C2 = 29.7 |
| C8a-S-C2-C(H) = 145.0 |
| S-C2-C(H)-C(H) = -5.1 |
| C2-C3-C1''-C2'' = 49.6 |
| C2-C(H)-C(H)-C(H) = -179.3 |
| C(H)-C(H)-C(H)-C1' = 178.1 |
| C(H)-C(H)-C1'-C2' = -1.0 |
| C3'-C4'-N-C(H$_3$) = 0.1 |
| C3'-C4'-N-C(H$_3$) = -179.9 |
| -1472.322197 (0.0) |
| Configuration | Image | \( C_2 \) Properties | Energy (kcal/mol) |
|---------------|-------|--------------------------|------------------|
| **Z, sp, E, c1.1** | ![Image](image1.png) | C4a-C8a-S-C2 = 26.3 <br> C8a-S-C2-C(H) = 148.1 <br> S-C2-C(H)-C(H) = -0.7 <br> C2-C3-C1"-C2" = 50.1 <br> C2-(2H)-C(H)-C(H) = 13.7 <br> C(H)-C(H)-C1'-C2' = -178.3 <br> C3'-C4'-N-C(H3) = -0.2 | -1472.678167 (4.9) | -1472.314945 (4.6) |
| **E, ap, Z, c1.1** | ![Image](image2.png) | C4a-C8a-S-C2 = 32.8 <br> C8a-S-C2-C(H) = 136.5 <br> S-C2-C(H)-C(H) = -174.8 <br> C2-C3-C1"-C2" = 45.1 <br> C2-(2H)-C(H)-C(H) = -176.4 <br> C(H)-C(H)-C1'-C2' = 15.1 <br> C(H)-C(H)-C1'-C2' = 22.8 <br> C3'-C4'-N-C(H3) = -0.2 | -1472.669332 (10.5) | -1472.306004 (10.2) |
| Conformation | bond lengths | energy | spin density |
|--------------|--------------|--------|--------------|
| $E, ap, Z, c1.2$ | C3'-C4'-N-C(H$_3$) = 177.0 | -1472.667582 (11.6) | -1472.304737 (11.0) |
| ![Chemical structure](image1.png) | C$_2$ | C4a-C8a-S-C2 = 32.5 |  
|  |  | C8a-S-C2-C(H) = 133.2 |  
|  |  | S-C2-C(H)-C(H) = 173.1 |  
|  |  | C2-C3-C1'-C2'' = 48.0 |  
|  |  | C2-C(H)-C(H)-C(H) = 172.8 |  
|  |  | C(H)-C(H)-C(H)-C1' = -11.7 |  
|  |  | C(H)-C(H)-C1'-C2' = -22.1 |  
|  |  | C3'-C4'-N-C(H$_3$) = 0.5 |  
|  |  | C3'-C4'-N-C(H$_3$) = -175.3 |  
| $E, +sc, Z, c1.1$ | C$_2$ | C4a-C8a-S-C2 = 33.4 |  
|  |  | C8a-S-C2-C(H) = 131.2 |  
|  |  | S-C2-C(H)-C(H) = 179.9 |  
|  |  | C2-C3-C1'-C2'' = 36.5 |  
|  |  | C2-C(H)-C(H)-C(H) = 42.8 |  
|  |  | C(H)-C(H)-C(H)-C1' = 8.1 |  
|  |  | C(H)-C(H)-C1'-C2' = 16.8 |  
| ![Chemical structure](image2.png) |  |  |  

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\[
\begin{align*}
C_3' - C_4' - N - C(H_3) &= 2.4 \\
C_3' - C_4' - N - C(H_3) &= 176.5 \\
\end{align*}
\]

**E, sp, Z, c1.1**

- C\(_2\)
- C\(_{4a}\)-C\(_{8a}\)-S-C\(_2\) = 26.3
- C\(_{8a}\)-S-C\(_2\)-C(H) = 154.2
- S-C\(_2\)-C(H)-C(H) = 147.3
- C\(_2\)-C\(_3\)-C\(_1'\)-C\(_2''\) = -56.1
- C\(_2\)-C(H)-C(H)-C\(_{1'}\) = -22.4
- C(H)-C(H)-C\(_{1'}\)-C\(_2'\) = -7.8
- C\(_3'\)-C\(_4'\)-N-C(H\(_3\)) = -0.4
- C\(_3'\)-C\(_4'\)-N-C(H\(_3\)) = -179.6

\[
\begin{align*}
\text{Energy} &= -1472.651845 (21.5) \\
\text{Energy} &= -1472.288135 (21.4)
\end{align*}
\]

**Z, ap, Z, c1.1**

- C\(_2\)
- C\(_{4a}\)-C\(_{8a}\)-S-C\(_2\) = 28.3
- C\(_{8a}\)-S-C\(_2\)-C(H) = 146.2
- S-C\(_2\)-C(H)-C(H) = 0.2
- C\(_2\)-C\(_3\)-C\(_1'\)-C\(_2''\) = 49.3
- C\(_2\)-C(H)-C(H)-C\(_{1'}\) = -176.4
- C(H)-C(H)-C(H)-C\(_{1'}\) = 12.8

\[
\begin{align*}
\text{Energy} &= -1472.677137 (5.6) \\
\text{Energy} &= -1472.313287 (5.6)
\end{align*}
\]
| Z, ap, Z, c1.2 | C(H)·C(H)·C1’·C2’ = 20.1  
C3’·C4’·N·C(H) = -0.6  
C3’·C4’·N·C(H) = 176.1 | C_2  
C4a·S·C2 = 28.3  
C8a·S·C2·C(H) = 146.1  
S·C2·C(H)·C(H) = -9.4  
C2·C3·C1’·C2’ = 51.0  
C2·C(H)·C(H)·C(H) = 179.1  
C(H)·C(H)·C(H)·C1’ = -14.7  
C(H)·C(H)·C1’·C2’ = -17.6  
C3’·C4’·N·C(H) = 0.3  
C3’·C4’·N·C(H) = -177.5 | -1472.677643 (5.3)  
-1472.313746 (5.3) |
| Z, +sc, Z, c1.1 | C_2  
C4a·S·C2 = 22.4  
C8a·S·C2·C(H) = 150.2  
S·C2·C(H)·C(H) = -0.4  
C2·C3·C1’·C2’ = 49.0  
C2·C(H)·C(H)·C(H) = 33.8 | -1472.668444 (11.0)  
-1472.303464 (11.8) |
| Structure | Bond Angles and Distances | Diprotonated form in methanol | E, ap, E, c1.1 |
|------------|--------------------------|-----------------------------|---------------|
| ![Structure](image1) | C(H)·C(H)·C(H)·C1' = 23.4  
C(H)·C(H)·C1'·C2' = 12.6  
C3'·C4'·N·C(H3) = 0.0  
C3'·C4'·N·C(H3) = 177.4 | -1472.666086 (12.5)  
-1472.301630 (12.9) | -1473.105767 (4.3)  
-1472.724850 (4.5) |
| ![Structure](image2) | C2  
C4a·C8a·S·C2 = 23.3  
C8a·S·C2·C(H) = 156.1  
S·C2·C(H)·C(H) = 7.6  
C2·C3·C1''·C2'' = 57.1  
C2·C(H)·C(H)·C(H) = -30.2  
C(H)·C(H)·C(H)·C1' = -17.8  
C(H)·C(H)·C1'·C2' = -13.9  
C3'·C4'·N·C(H3) = 0.1  
C3'·C4'·N·C(H3) = -177.0 | | |
|      | C2-C3-C1''-C2'' = 42.2 |
|------|------------------------|
|      | C2-C(H)-C(H)-C(H) = -179.5 |
|      | C(H)-C(H)-C(H)-C1' = 179.8 |
|      | C(H)-C(H)-C1'-C2' = -6.8 |
|      | C3'-C4''-N-C(H3) = 117.4 |
|      | C3'-C4''-N-C(H3) = -115.2 |

$E$, $ap$, $E$, c1.2

|      | C2 |
|------|---|
|      | C4a-C8a-S-C2 = 30.9 |
|      | C8a-S-C2-C(H) = 133.7 |
|      | S-C2-C(H)-C(H) = 178.9 |
|      | C2-C3-C1''-C2'' = 40.4 |
|      | C2-C(H)-C(H)-C(H) = -179.0 |
|      | C(H)-C(H)-C(H)-C1' = -178.8 |
|      | C(H)-C(H)-C1'-C2' = -0.5 |
|      | C3'-C4''-N-C(H3) = 121.1 |
|      | C3'-C4''-N-C(H3) = -111.7 |

$E$, $ap$, $E$, c1.3

|      | C2 |
|------|---|
|      | C4a-C8a-S-C2 = 30.5 |
|      | C8a-S-C2-C(H) = 134.7 |

$-1473.105857 (4.3)$

$-1472.725447 (4.1)$
$S\text{-}C2\text{-}C(H)\text{-}C(H) = 178.1$
$C2\text{-}C3\text{-}C1''\text{-}C2'' = 41.4$
$C2\text{-}C(H)\text{-}C(H)\text{-}C(H) = -178.1$
$C(H)\text{-}C(H)\text{-}C(H)\text{-}C1' = -179.9$
$C(H)\text{-}C(H)\text{-}C1'\text{-}C2' = 2.2$
$C3'\text{-}C4'\text{-}N\text{-}C(H_3) = 114.2$
$C3'\text{-}C4'\text{-}N\text{-}C(H_3) = -118.4$

$E, +sc, E, c1.1$

$C_2$
$C4a\text{-}C8a\text{-}S\text{-}C2 = 32.4$
$C8a\text{-}S\text{-}C2\text{-}C(H) = 130.2$
$S\text{-}C2\text{-}C(H)\text{-}C(H) = -176.1$
$C2\text{-}C3\text{-}C1''\text{-}C2'' = 32.7$
$C2\text{-}C(H)\text{-}C(H)\text{-}C(H) = 37.2$
$C(H)\text{-}C(H)\text{-}C(H)\text{-}C1' = 178.1$
$C(H)\text{-}C(H)\text{-}C1'\text{-}C2' = 8.0$
$C3'\text{-}C4'\text{-}N\text{-}C(H_3) = 115.2$
$C3'\text{-}C4'\text{-}N\text{-}C(H_3) = -117.4$

$\text{-1473.096876 (9.9)}$
$\text{-1472.716653 (9.6)}$
| $Z, +ac, E, c1.1$ | $C_2$ | $-1473.112666 (0.0)$ | $-1472.731167 (0.5)$ |
|---|---|---|---|
| &nbsp; | C4a-C8a-S-C2 = 27.1 | &nbsp; | &nbsp; |
| &nbsp; | C8a-S-C2-(C(H) = 144.7 | &nbsp; | &nbsp; |
| &nbsp; | S-C2-(C(H)-(C(H) = -7.2 | &nbsp; | &nbsp; |
| &nbsp; | C2-C3-C1''-C2'' = 46.7 | &nbsp; | &nbsp; |
| &nbsp; | C2-(C(H)-(C(H)-(C(H) = 117.8 | &nbsp; | &nbsp; |
| &nbsp; | C(H)-(C(H)-(C(H)-(C1' = 178.4 | &nbsp; | &nbsp; |
| &nbsp; | C(H)-(C(H)-(C1'-C2' = -4.4 | &nbsp; | &nbsp; |
| &nbsp; | C3'-C4'-N-(C(H3) = 113.5 | &nbsp; | &nbsp; |
| &nbsp; | C3'-C4'-N-(C(H3) = -119.0 | &nbsp; | &nbsp; |

| $Z, ap, E, c1.1$ | $C_2$ | $-1473.112598 (0.0)$ | $-1472.731951 (0.0)$ |
|---|---|---|---|
| &nbsp; | C4a-C8a-S-C2 = 27.4 | &nbsp; | &nbsp; |
| &nbsp; | C8a-S-C2-(C(H) = 143.8 | &nbsp; | &nbsp; |
| &nbsp; | S-C2-(C(H)-(C(H) = -7.6 | &nbsp; | &nbsp; |
| &nbsp; | C2-C3-C1''-C2'' = 46.1 | &nbsp; | &nbsp; |
| &nbsp; | C2-(C(H)-(C(H)-(C(H) = 178.8 | &nbsp; | &nbsp; |
| &nbsp; | C(H)-(C(H)-(C(H)-(C1' = 177.6 | &nbsp; | &nbsp; |
| &nbsp; | C(H)-(C(H)-(C1'-C2' = -1.3 | &nbsp; | &nbsp; |
| &nbsp; | C3'-C4'-N-(C(H3) = 117.6 | &nbsp; | &nbsp; |
| Configuration | Chemical Structure | Bonds and Angles | Z score 1 | Z score 2 |
|---------------|-------------------|-----------------|----------|----------|
| Z, sp, E, c1.1 | ![Chemical Structure](image1) | C3'–C4'–N–C(H₃) = -115.0 | -1473.105761 (4.3) | -1472.725512 (4.0) |
|                |                   | C₂               |          |          |
|                |                   | C4a-C8a-S-C2 = 23.1 |          |          |
|                |                   | C8a-S-C2-C(H) = 147.8 |          |          |
|                |                   | S-C2-C(H)-C(H) = -4.3 |          |          |
|                |                   | C2-C3-C1''-C2'' = 46.8 |          |          |
|                |                   | C2-(H)-C(H)-C(H) = 21.4 |          |          |
|                |                   | C(H)-C(H)-C(H)-C1' = -178.1 |          |          |
|                |                   | C(H)-C(H)-C1'-C2' = 2.0 |          |          |
|                |                   | C3'-C4'-N-C(H₃) = 112.3 |          |          |
|                |                   | C3'-C4'-N-C(H₃) = -120.1 |          |          |
| Z, sp, E, c1.2 | ![Chemical Structure](image2) | C₂               | -1473.106013 (4.2) | -1472.724967 (4.4) |
|                |                   | C4a-C8a-S-C2 = 24.4 |          |          |
|                |                   | C8a-S-C2-C(H) = 145.2 |          |          |
|                |                   | S-C2-C(H)-C(H) = -4.3 |          |          |
|                |                   | C2-C3-C1''-C2'' = 45.9 |          |          |
|                |                   | C2-(H)-C(H)-C(H) = 26.1 |          |          |
|                |                   | C(H)-C(H)-C(H)-C1' = -177.1 |          |          |
|                |                   | C(H)-C(H)-C1'-C2' = 13.6 |          |          |
| Z, sp, E, c1.3 | C2  |
|----------------|-----|
| 4a-C8a-S-C2 = 24.0 |   |
| C8a-S-C2-C(H) = 146.1 |   |
| S-C2-C(H)-C(H) = -4.3 |   |
| C2-C3-C1'-C2' = 46.3 |   |
| C2-C(H)-C(H)-C(H) = 24.6 |   |
| C(H)-C(H)-C(H)-C1' = -177.2 |   |
| C(H)-C(H)-C1'-C2' = 9.4 |   |
| C3'-C4'-N-C(H3) = 112.6 |   |
| C3'-C4'-N-C(H3) = -119.8 |   |
| C2-C8a-S-C2 = 30.6 | C2  |
| C8a-S-C2-C(H) = 134.7 |   |
| S-C2-C(H)-C(H) = -177.7 |   |
| C2-C3-C1'-C2' = 39.9 |   |
| C2-C(H)-C(H)-C(H) = -174.4 |   |
| C(H)-C(H)-C(H)-C1' = 9.3 |   |

-1473.099714 (8.1) | -1472.717146 (9.3)
| $E, ap, Z, c1.2$ | \[
\begin{align*}
\text{C(H)} \cdot \text{C(H)} \cdot \text{C}^{'-}\text{C}^{''} &= 37.3 \\
\text{C}^{'}\text{C}^{''} \cdot \text{N} \cdot \text{C(H)} &= 119.2 \\
\text{C}^{'}\text{C}^{''} \cdot \text{N} \cdot \text{C(H)} &= -113.4
\end{align*}
| \[
\begin{align*}
\text{C}^{'}\text{C}^{''} \cdot \text{N} \cdot \text{C(H)} &= 110.8 \\
\text{C}^{'}\text{C}^{''} \cdot \text{N} \cdot \text{C(H)} &= -121.9
\end{align*}
| \[
\begin{align*}
\text{C}^{'}\text{C}^{''} \cdot \text{N} \cdot \text{C(H)} &= 110.8 \\
\text{C}^{'}\text{C}^{''} \cdot \text{N} \cdot \text{C(H)} &= -121.9
\end{align*}
| \[
\begin{align*}
\text{C}^{'}\text{C}^{''} \cdot \text{N} \cdot \text{C(H)} &= 110.8 \\
\text{C}^{'}\text{C}^{''} \cdot \text{N} \cdot \text{C(H)} &= -121.9
\end{align*}
|  
| $C_2$ |  
\[
\begin{align*}
\text{C}^{4a} \cdot \text{C}^{8a} \cdot \text{S} \cdot \text{C}^{2} &= 30.1 \\
\text{C}^{8a} \cdot \text{S} \cdot \text{C}^{2} \cdot \text{C(H)} &= 135.7 \\
\text{S} \cdot \text{C}^{2} \cdot \text{C(H)} \cdot \text{C(H)} &= -178.7 \\
\text{C}^{2} \cdot \text{C}^{3} \cdot \text{C}^{1''} \cdot \text{C}^{2''} &= 40.8 \\
\text{C}^{2} \cdot \text{C(H)} \cdot \text{C(H)} \cdot \text{C(H)} &= -173.0 \\
\text{C(H)} \cdot \text{C(H)} \cdot \text{C(H)} \cdot \text{C}^{1'} &= 8.8 \\
\text{C(H)} \cdot \text{C(H)} \cdot \text{C}^{1''} \cdot \text{C}^{2''} &= 34.4 \\
\text{C}^{'}\text{C}^{''} \cdot \text{N} \cdot \text{C(H)} &= 110.8 \\
\text{C}^{'}\text{C}^{''} \cdot \text{N} \cdot \text{C(H)} &= -121.9
\end{align*}
| -1473.099802 (8.1) | -1472.718777 (8.3) |
|  $E, ap, Z, c1.3$ |  
|---|---|
| ![Chemical Structure](image) | C₂  
C₄a-C₈a-S-C₂ = 30.5  
C₈a-S-C₂-C(H) = 130.7  
S-C₂-C(H)-C(H) = 176.4  
C₂-C₃-C₁"-C₂" = 39.4  
C₂-C(H)-C(H)-C(H) = 172.6  
C(H)-C(H)-C₁'-C₂' = -38.8  
C₃'-C₄'-N-C(H₃) = 120.2  
C₃'-C₄'-N-C(H₃) = -38.8  
\[ \text{Energy: } -1473.098430 (8.9) \] |
|  $E, ap, Z, c1.4$ | C₂  
C₄a-C₈a-S-C₂ = 30.3  
C₈a-S-C₂-C(H) = 131.2  
S-C₂-C(H)-C(H) = 175.7  
C₂-C₃-C₁"-C₂" = 40.8  
C₂-C(H)-C(H)-C(H) = 171.5  
C(H)-C(H)-C₁'-C₂' = -37.9  
C₃'-C₄'-N-C(H₃) = 120.2  
\[ \text{Energy: } -1472.718403 (8.5) \] |
|    | C3’-C4’-N-C(H) = -112.2 |
|----|------------------------|
| **E, +sc, Z, c1.1** | |
| ![Chemical Structure](image) | C2 |
| C4a-C8a-S-C2 = 31.6 | |
| C8a-S-C2-C(H) = 129.9 | |
| S-C2-C(H)-C(H) = 178.4 | |
| C2-C3-C1”-C2” = 33.4 | |
| C2-C(H)-C(H)-C(H) = 57.4 | |
| C(H)-C(H)-C1’-C1’ = 2.5 | |
| C(H)-C(H)-C1’-C2’ = 33.6 | |
| C3’-C4’-N-C(H) = 110.7 | |
| C3’-C4’-N-C(H) = -121.7 | |
| **Z, op, Z, c1.1** | C2 |
| ![Chemical Structure](image) | |
| C4a-C8a-S-C2 = 25.9 | |
| C8a-S-C2-C(H) = 146.0 | |
| S-C2-C(H)-C(H) = -3.0 | |
| C2-C3-C1”-C2” = 46.2 | |
| C2-C(H)-C(H)-C(H) = -178.4 | |
| C(H)-C(H)-C(H)-C1’ = 6.1 | |
| C(H)-C(H)-C1’-C2’ = 38.9 | |
| Structure | Bond Length (Å) | Energy (kcal/mol) |
|-----------|----------------|------------------|
| **Z, ap, Z, c1.2** | C3'-C4'-N-C(H3) = 113.3 | -1473.106323 (4.0) |
| | C3'-C4'-N-C(H3) = -119.4 | -1472.724393 (4.7) |
| ![Structure Image](image1.png) | C2 | 1473.106216 (4.0) |
| | C4a-C8a-S-C2 = 26.4 | -1472.725287 (4.2) |
| | C8a-S-C2-C(H) = 144.1 |  |
| | S-C2-C(H)-C(H) = -11.6 |  |
| | C2-C3-C1"-C2" = 47.8 |  |
| | C2-C(H)-C(H)-C(H) = 175.9 |  |
| | C(H)-C(H)-C(H)-C1' = -9.9 |  |
| | C(H)-C(H)-C1'-C2' = -36.1 |  |
| | C3'-C4'-N-C(H3) = 115.9 |  |
| | C3'-C4'-N-C(H3) = -116.8 |  |
| **Z, ap, Z, c1.3** | C2 | 1473.106216 (4.0) |
| | C4a-C8a-S-C2 = 26.4 | -1472.725287 (4.2) |
| | C8a-S-C2-C(H) = 144.2 |  |
| | S-C2-C(H)-C(H) = -11.0 |  |
| | C2-C3-C1"-C2" = 47.7 |  |
| | C2-C(H)-C(H)-C(H) = 175.2 |  |
| | C(H)-C(H)-C(H)-C1' = -9.4 |  |
| Configuration   | Structure | Bond Angles (°) | Energies (kcal/mol) |
|-----------------|-----------|----------------|---------------------|
| Z, +sc, Z, c1.1 | ![Structure](image1.png) | C(H)-C(H)-C1'-C2' = -33.8  
C3'-C4'-N-C(H3) = 121.1  
C3'-C4'-N-C(H3) = -111.4 | -1473.098551 (8.9)  
-1472.716979 (9.4) |
| Z, +sc, Z, c1.2 | ![Structure](image2.png) | C(H)-C(H)-C1'-C2' = -33.8  
C3'-C4'-N-C(H3) = 121.1  
C3'-C4'-N-C(H3) = -111.4 | -1473.098545 (8.9)  
-1472.717244 (9.2) |
|                  | 1473.095385 (10.8) | -1472.714509 (10.9) |
|------------------|---------------------|----------------------|
| **Z, -sc, Z, c1.1** |                     |                      |
| ![Chemical Structure](image) | ![Chemical Structure](image) |                      |
| **C(H)-C(H)-C(H)-C1’ = 13.7** |                     |                      |
| **C(H)-C(H)-C1’-C2’ = 25.5** |                     |                      |
| **C3’-C4’-N-C(H3) = 118.1** |                     |                      |
| **C3’-C4’-N-C(H3) = -114.5** |                     |                      |
| **C4a-C8a-S-C2 = 22.7** |                     |                      |
| **C8a-S-C2-C(H) = 152.4** |                     |                      |
| **S-C2-C(H)-C(H) = -3.3** |                     |                      |
| **C2-C3-C1’-C2” = 49.7** |                     |                      |
| **C2-C(H)-C(H)-C(H) = -47.8** |                     |                      |
| **C(H)-C(H)-C(H)-C1’ = -6.5** |                     |                      |
| **C(H)-C(H)-C1’-C2’ = -29.0** |                     |                      |
| **C3’-C4’-N-C(H3) = 113.5** |                     |                      |
| **C3’-C4’-N-C(H3) = -118.8** |                     |                      |
### Table 3.4.

| Isomer / conformer | Schematic drawing | $\lambda$ / nm ($f$): orbitalic contribution (expansion coefficient)* |
|--------------------|-------------------|---------------------------------------------------------------|
| Neutral form in methanol | ![Schematic drawing](image) |                                                                 |

* Represents the expansion coefficient for the orbitalic contribution.

**Table 3.4.** 3-Phenylbenzothiazine: electronic transitions [TD-PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)] for the most stable structures identified, and isodensity maps (0.04 a.u.) of selected molecular orbitals.
$Z,\ ap, E, c1.1$

|   |   |
|---|---|
| ![Chemical Structure](image) | ![Chemical Structure](image) |

### Energies (eV)

- **506.0 (0.78):** $101 \rightarrow 102 (0.69)$
- **384.4 (0.77):** $100 \rightarrow 102 (0.17)$; $100 \rightarrow 103 (0.12)$; $101 \rightarrow 102 (-0.12)$; **$101 \rightarrow 103 (0.66)$**
- **371.1 (0.11):** $100 \rightarrow 102 (0.67)$; $101 \rightarrow 103 (-0.18)$
- **329.3 (0.08):** $94 \rightarrow 102 (-0.13)$; $95 \rightarrow 102 (0.16)$; $99 \rightarrow 102 (0.62)$; $101 \rightarrow 104 (-0.20)$
- **310.2 (0.09):** $97 \rightarrow 102 (-0.15)$; $101 \rightarrow 104 (-0.26)$; $101 \rightarrow 105 (-0.34)$; $101 \rightarrow 106 (0.50)$
- **307.3 (0.03):** $94 \rightarrow 102 (-0.13)$; $95 \rightarrow 102 (0.12)$; $96 \rightarrow 102 (0.11)$; $99 \rightarrow 102 (0.13)$; $100 \rightarrow 104 (0.12)$; $101 \rightarrow 104 (0.57)$; $101 \rightarrow 105 (-0.16)$; $101 \rightarrow 106 (0.21)$

### HOMO Energies

- **#97, HOMO-4 (-0.27524)$^\text{b}$**
- **#98, HOMO-3 (-0.26881)**
- **#99, HOMO-2 (-0.25370)**
- **#100, HOMO-1 (-0.22815)**
- **#101, HOMO (-0.19309)**
| #102, LUMO (-0.08338) | #103, LUMO+1 (-0.05014) | #104, LUMO+2 (-0.02090) | #105, LUMO+3 (-0.01932) | #106, LUMO+4 (-0.01496) |
|------------------------|------------------------|------------------------|------------------------|------------------------|

Monoprotonated (iminium) form in methanol

Z, ap, E, c1.1

| 616.2 (1.01): 100 → 102 (0.14); 101 → 102 (0.69) |
| 441.3 (0.44): 100 → 102 (0.68); 101 → 102 (-0.15) |
| 378.2 (0.37): 100 → 103 (0.13); 101 → 103 (0.68) |
| 344.4 (0.16): 99 → 102 (0.68); 101 → 104 (-0.12) |
| 328.4 (0.08): 98 → 102 (0.67); 100 → 103 (-0.13) |
| 324.7 (0.00): 97 → 102 (0.69); 101 → 107 (0.12) |
| 323.3 (0.00): 96 → 102 (0.70) |
| 305.1 (0.10): 99 → 102 (0.12); 100 → 103 (-0.13); 100 → 104 (0.13); 101 → 104 (0.65) |
| #97, HOMO-4 (-0.29055) | #98, HOMO-3 (-0.28572) | #99, HOMO-2 (-0.27923) | #100, HOMO-1 (-0.24596) | #101, HOMO (-0.21145) |
|------------------------|------------------------|------------------------|------------------------|------------------------|
| #102, LUMO (-0.12248)  | #103, LUMO+1 (-0.06562)| #104, LUMO+2 (-0.03635)| #105, LUMO+3 (-0.03436)| #106, LUMO+4 (-0.03072)|

Diprotonated form in methanol
| Z, +ac, E, c1.1 | ![Structure Image] | **554.4 (0.42): 101 → 102 (0.70)** |
|----------------|------------------|----------------------------------|
|                |                  | **379.7 (0.39): 100 → 102 (0.67)**; 101 → 103 (-0.18) |
|                |                  | **363.0 (0.28): 99 → 102 (0.67)**; 100 → 102 (-0.10); 101 → 103 (-0.15) |
|                |                  | **356.4 (0.61): 99 → 102 (0.18); 100 → 102 (0.15); 101 → 102 (-0.12); 101 → 103 (0.65)** |
|                |                  | 346.9 (0.00): 98 → 102 (0.70) |
|                |                  | 311.4 (0.00): 97 → 102 (0.68); 101 → 104 (0.14) |
|                |                  | 302.8 (0.07): 96 → 102 (0.68) |

| ![Image 1] | ![Image 2] | ![Image 3] | ![Image 4] | ![Image 5] |
|------------|------------|------------|------------|------------|
| #97, HOMO-4 (-0.30799) | #98, HOMO-3 (-0.29867) | #99, HOMO-2 (-0.28829) | #100, HOMO-1 (-0.28381) | #101, HOMO (-0.24196) |
#102, LUMO (-0.13686)  #103, LUMO+1 (-0.08440)  #104, LUMO+2 (-0.04938)  #105, LUMO+3 (-0.04386)  #106, LUMO+4 (-0.04193)

[a] Only transitions above 300 nm are reported. Transitions with $f > 0.1$ are highlighted, along with their main orbitalic contributions.

[b] Orbital energies in hartrees.

**Figure 3.4.** 3-Phenylbenzothiazine: plot of selected orbital energies [PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)]
Figure 3.5. 3-Phenylbenzothiazine: TD-PBE0 calculations
Figure 3.6. 3-Phenylbenzothiazine: TD-M06-2X calculations
Part 4. Cyanines derived from condensation of 1,4-benzothiazines with vanillin

Table 4.1. 3-Methylbenzothiazine: conformational exploration

| Isomer / conformer | Schematic drawing | Symmetry | Selected dihedrals / deg | $E$ or $G_{\text{PCM}}$ / hartree ($\Delta E$ or $\Delta G_{\text{PCM}}$ / kcal mol$^{-1}$) | $G_{\text{RRHO}}$ or $G_{\text{PCM,RRHO}}$ / hartree ($\Delta G_{\text{RRHO}}$ or $\Delta G_{\text{PCM,RRHO}}$ / kcal mol$^{-1}$) |
|-------------------|-------------------|----------|--------------------------|-----------------------------------------------|-----------------------------------------------------------------|
| $E$, c1.1         | ![Neutral form in vacuo](image) | $C_2$ | C4a-C8a-S-C2 = 28.0, C8a-C2-C(H) = 131.6, S-C2-C(H)-C1' = -176.6, C2-C(H)-C1'-C2' = 33.0, C2'-C3'-O-C(H$_3$) = -0.4, C3'-C4'-O-H = -0.1 | -1259.108777 (3.9) | -1258.872751 (4.4) |
| $E$, c1.2         | ![Neutral form in vacuo](image) | $C_2$ | C4a-C8a-S-C2 = 27.8, C8a-C2-C(H) = 132.1, S-C2-C(H)-C1' = -177.1, C2-C(H)-C1'-C2' = -149.4 | -1259.108071 (4.3) | -1258.872303 (4.6) |
| Z, c1.1 | C2'-C3'-O-C(H₃) = -0.6  
C3'-C4'-O-H = 0.1 |
|---------|-------------------------|
| ![Diagram](image1.png) | C₂ |
| C4a-C8a-S-C2 = 14.1  
C8a-S-C2-C(H) = 163.8  
S-C2-C(H)-C1' = -5.8  
C2-C(H)-C1'-C2' = 0.8  
C2'-C3'-O-C(H₃) = 0.0  
C3'-C4'-O-H = -0.3 |
| -1259.114935 (0.0) | -1258.879696 (0.0) |
| Z, c1.2 | C₂ |
| ![Diagram](image2.png) | C₂ |
| C4a-C8a-S-C2 = 12.3  
C8a-S-C2-C(H) = 163.9  
S-C2-C(H)-C1' = -3.1  
C2-C(H)-C1'-C2' = -161.3  
C2'-C3'-O-C(H₃) = 0.0  
C3'-C4'-O-H = 0.3 |
| -1259.114174 (0.5) | -1258.878484 (0.8) |

Neutral form in methanol
| Configuration | Image | Bond Angles | Energy (kcal/mol) |
|---------------|-------|-------------|------------------|
| $E, c1.1$     | ![Image](image1.png) | C1:  
- C4a-C8a-S-C2 = 28.5  
- C8a-S-C2-C(H) = 131.1  
- S-C2-C(H)-C1' = -176.9  
- C2-C(H)-C1'-C2' = -150.6  
- C2'-C3'-O-C(H$_3$) = -0.5  
- C3'-C4'-O-H = 0.1  
| $E, c1.2$     | ![Image](image2.png) | C1:  
- C4a-C8a-S-C2 = 28.5  
- C8a-S-C2-C(H) = 131.1  
- S-C2-C(H)-C1' = -176.9  
- C2-C(H)-C1'-C2' = -150.6  
- C2'-C3'-O-C(H$_3$) = -0.5  
- C3'-C4'-O-H = 0.1  
| $Z, c1.1$     | ![Image](image3.png) | C1:  
- C4a-C8a-S-C2 = 15.6  
- C8a-S-C2-C(H) = 160.4  
- S-C2-C(H)-C1' = -5.0  
- C2-C(H)-C1'-C2' = 14.3  

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| Z, c1.2 | C2'–C3'–O–C(\(\text{H}_3\)) = -0.7  
C3'–C4'–O–H = -0.2 |
|---------|------------------|
| ![Image](image1.png) | C\(_2\)  
C\(_{4a}\)-C\(_{8a}\)-S-C\(_2\) = 15.7  
C\(_{8a}\)-S-C\(_2\)-C(\(\text{H}\)) = 160.2  
S-C\(_2\)-C(\(\text{H}\))-C\(_1'\) = -5.0  
C\(_2\)-C(\(\text{H}\))-C\(_1'\)-C\(_2'\) = 13.6  
C\(_2'\)-C\(_3'\)-O–C(\(\text{H}_3\)) = -0.7  
C\(_3'\)-C\(_4'\)-O–H = -0.3 |
| -1259.126139 (0.0) | -1258.891080 (0.0) |

Monoprotonated (iminium) form in methanol

| E, c1.1 | C\(_2\)  
C\(_{4a}\)-C\(_{8a}\)-S-C\(_2\) = 32.9  
C\(_{8a}\)-S-C\(_2\)-C(\(\text{H}\)) = 134.5  
S-C\(_2\)-C(\(\text{H}\))-C\(_1'\) = -176.3  
C\(_2\)-C(\(\text{H}\))-C\(_1'\)-C\(_2'\) = 28.1  
C\(_2'\)-C\(_3'\)-O–C(\(\text{H}_3\)) = 0.2  
C\(_3'\)-C\(_4'\)-O–H = -0.4 |
|---------|------------------|
| ![Image](image2.png) | -1259.563233 (6.5) | -1259.314330 (5.9) |
| $E$, c1.2 | ![Chemical Structure](image) | $C_1$ | -1259.560577 (8.2) | -1259.310137 (8.5) |
| --- | --- | --- | --- | --- |
| | $C4a$,$C8a$-$S$-$C2$ = 24.9 | $C8a$-$S$-$C2$-$C(H)$ = 148.2 | $S$-$C2$-$C(H)$-$C1'$ = 150.1 |
| | $C2$-$C(H)$-$C1'$-$C2'$ = -31.3 | $C2'$-$C3'$-$O$-$C(H_3)$ = -0.5 | $C3'$-$C4'$-$O$-$H$ = 0.2 |

| $E$, c1.3 | ![Chemical Structure](image) | $C_2$ | -1259.563748 (6.2) | -1259.313756 (6.2) |
| --- | --- | --- | --- | --- |
| | $C4a$-$C8a$-$S$-$C2$ = 32.8 | $C8a$-$S$-$C2$-$C(H)$ = 135.0 | $S$-$C2$-$C(H)$-$C1'$ = -175.5 |
| | $C2$-$C(H)$-$C1'$-$C2'$ = -151.2 | $C2'$-$C3'$-$O$-$C(H_3)$ = -0.7 | $C3'$-$C4'$-$O$-$H$ = 0.2 |

| $E$, c1.4 | ![Chemical Structure](image) | $C_2$ | -1259.561121 (7.8) | -1259.311563 (7.6) |
| --- | --- | --- | --- | --- |
| | $C4a$-$C8a$-$S$-$C2$ = 24.6 | $C8a$-$S$-$C2$-$C(H)$ = 148.6 | $S$-$C2$-$C(H)$-$C1'$ = 150.1 |
| | $C2$-$C(H)$-$C1'$-$C2'$ = 152.2 | $C2$-$C(H)$-$C1'$-$C2'$ = 152.2 | $C2$-$C(H)$-$C1'$-$C2'$ = 152.2 |
|    |    | C2'-C3'-O-C(H₃) = 0.5 | C3'-C4'-O-H = -0.3 |
|----|----|----------------------|------------------|
| Z, c1.1 | ![Chemical Structure](image1) | C₂ |
|        | ![Chemical Structure](image2) | C₄a-C8a-S-C₂ = 20.7 |
|        | ![Chemical Structure](image3) | C₈a-S-C₂-C(H) = 159.7 |
|        | ![Chemical Structure](image4) | S-C₂-C(H)-C₁' = -8.0 |
|        | ![Chemical Structure](image5) | C₂-C(H)-C₁'-C₂' = -0.6 |
|        | ![Chemical Structure](image6) | C₂'-C₃'-O-C(H₃) = 0.2 |
|        | ![Chemical Structure](image7) | C₃'-C₄'-O-H = -0.4 |
| Z, c1.2 | ![Chemical Structure](image8) | C₂ |
|        | ![Chemical Structure](image9) | C₄a-C8a-S-C₂ = 17.4 |
|        | ![Chemical Structure](image10) | C₈a-S-C₂-C(H) = 162.4 |
|        | ![Chemical Structure](image11) | S-C₂-C(H)-C₁' = -4.6 |
|        | ![Chemical Structure](image12) | C₂-C(H)-C₁'-C₂' = -173.0 |
|        | ![Chemical Structure](image13) | C₂'-C₃'-O-C(H₃) = -0.4 |
|        | ![Chemical Structure](image14) | C₃'-C₄'-O-H = 0.1 |

Monoanionic (phenate) form in methanol
| $E, \text{c1.1}$ | ![Chemical Structure] | $C_1$ | $\text{C4a-C8a-S-C2} = 31.3$ | $\text{C8a-S-C2-C(H)} = 129.4$ | $\text{S-C2-C(H)-C1'} = -173.8$ | $\text{C2-C(H)-C1'-C2'} = 20.0$ | $\text{C2'-C3'-O-C(H_3)} = -0.6$ | $-1258.641246 \ (4.8)$ | $-1258.418590 \ (4.7)$ |
| $E, \text{c1.2}$ | ![Chemical Structure] | $C_2$ | $\text{C4a-C8a-S-C2} = 30.9$ | $\text{C8a-S-C2-C(H)} = 129.6$ | $\text{S-C2-C(H)-C1'} = -174.6$ | $\text{C2-C(H)-C1'-C2'} = 21.7$ | $\text{C2'-C3'-O-C(H_3)} = 115.0$ | $-1258.638963 \ (6.3)$ | $-1258.416545 \ (6.0)$ |
| $E, \text{c1.3}$ | ![Chemical Structure] | $C_2$ | $\text{C4a-C8a-S-C2} = 30.8$ | $\text{C8a-S-C2-C(H)} = 130.2$ | $\text{S-C2-C(H)-C1'} = -174.8$ | $\text{C2-C(H)-C1'-C2'} = 22.2$ | $\text{C2'-C3'-O-C(H_3)} = -112.3$ | $-1258.638759 \ (6.4)$ | $-1258.417200 \ (5.6)$ |
| $E$, c1.4 | ![Chemical Structure] | $C_1$ | -1258.634365 (9.1) | -1258.412885 (8.3) |
| --- | --- | --- | --- | --- |
| | | C4a-C8a-S-C2 = 24.8 | | |
| | | C8a-S-C2-C(H) = 143.2 | | |
| | | S-C2-C(H)-C1’ = 156.5 | | |
| | | C2-C(H)-C1’-C2’ = -31.0 | | |
| | | C2’-C3’-O-(H$_3$) = 0.1 | | |

| $E$, c1.5 | ![Chemical Structure] | $C_2$ | -1258.632090 (10.6) | -1258.411137 (9.4) |
| --- | --- | --- | --- | --- |
| | | C4a-C8a-S-C2 = 26.2 | | |
| | | C8a-S-C2-C(H) = 137.8 | | |
| | | S-C2-C(H)-C1’ = 162.4 | | |
| | | C2-C(H)-C1’-C2’ = -34.2 | | |
| | | C2’-C3’-O-(H$_3$) = 112.7 | | |

| $E$, c1.6 | ![Chemical Structure] | $C_2$ | -1258.632382 (10.4) | -1258.411378 (9.3) |
| --- | --- | --- | --- | --- |
| | | C4a-C8a-S-C2 = 25.5 | | |
| | | C8a-S-C2-C(H) = 139.9 | | |
| | | S-C2-C(H)-C1’ = 160.2 | | |
| | | C2-C(H)-C1’-C2’ = -35.2 | | |
| | | C2’-C3’-O-(H$_3$) = -116.2 | | |
| $E$, c1.7 | ![Chemical Structure](image1) | $C_1$ | $-1258.640855 (5.1)$ | $-1258.418592 (4.7)$ |
| --- | --- | --- | --- | --- |
| C4a-C8a-S-C2 = 31.0 | C8a-S-C2-C(H) = 129.8 | S-C2-C(H)-C1’ = -174.2 | C2-C(H)-C1’-C2’ = -160.1 | C2’-C3’-O-(H3) = -0.1 |
| $E$, c1.8 | ![Chemical Structure](image2) | $C_2$ | $-1258.638693 (6.4)$ | $-1258.417722 (5.3)$ |
| --- | --- | --- | --- | --- |
| C4a-C8a-S-C2 = 30.9 | C8a-S-C2-C(H) = 129.7 | S-C2-C(H)-C1’ = -174.7 | C2-C(H)-C1’-C2’ = -160.4 | C2’-C3’-O-(H3) = 115.0 |
| $E$, c1.9 | ![Chemical Structure](image3) | $C_2$ | $-1258.638695 (6.4)$ | $-1258.417292 (5.6)$ |
| --- | --- | --- | --- | --- |
| C4a-C8a-S-C2 = 30.9 | C8a-S-C2-C(H) = 130.0 | S-C2-C(H)-C1’ = -174.5 | C2-C(H)-C1’-C2’ = -160.3 | C2’-C3’-O-(H3) = -115.1 |
| E, c1.10 | ![Chemical Structure](image1) | $C_1$ | -1258.634598 (9.0) | -1258.412105 (8.8) |
|---|---|---|---|---|
| | C4a-C8a-S-C2 = 24.8 | C8a-S-C2-C(H) = 143.1 |
| | S-C2-C(H)-C1' = 157.3 | C2-C(H)-C1'-C2' = 151.8 |
| | C2'-C3'-O-C(H$_3$) = 0.4 |  |

| E, c1.11 | ![Chemical Structure](image2) | $C_2$ | -1258.632253 (10.5) | -1258.410920 (9.6) |
|---|---|---|---|---|
| | C4a-C8a-S-C2 = 24.3 | C8a-S-C2-C(H) = 142.7 |
| | S-C2-C(H)-C1' = 157.7 | C2-C(H)-C1'-C2' = 150.5 |
| | C2'-C3'-O-C(H$_3$) = 115.6 |  |

| E, c1.12 | ![Chemical Structure](image3) | $C_2$ | -1258.632329 (10.4) | -1258.411858 (9.0) |
|---|---|---|---|---|
| | C4a-C8a-S-C2 = 24.6 | C8a-S-C2-C(H) = 142.2 |
| | S-C2-C(H)-C1' = 158.7 | C2-C(H)-C1'-C2' = 149.5 |
| | C2'-C3'-O-C(H$_3$) = -115.6 |  |
| Z, c1.1 | C₂ | $-1258.64936 \ (0.0)$ | $-1258.426129 \ (0.0)$ |
|---------|----|---------------------|---------------------|
| ![Chemical Structure](image1) | C⁴a-C⁸a-S-C₂ = 20.5 | C⁸a-S-C₂-C(H) = 158.7 |
| | S-C₂-C(H)-C₁' = -6.4 | C₂-C(H)-C₁'-C₂' = -0.5 |
| | C₂'-C₃'-O-C(H₃) = -0.4 | |

| Z, c1.2 | C₂ | $-1258.646560 \ (1.5)$ | $-1258.424496 \ (1.0)$ |
|---------|----|---------------------|---------------------|
| ![Chemical Structure](image2) | C⁴a-C⁸a-S-C₂ = 18.9 | C⁸a-S-C₂-C(H) = 158.8 |
| | S-C₂-C(H)-C₁' = -4.2 | C₂-C(H)-C₁'-C₂' = 8.1 |
| | C₂'-C₃'-O-C(H₃) = 114.4 | |

| Z, c1.3 | C₂ | $-1258.646565 \ (1.5)$ | $-1258.424456 \ (1.1)$ |
|---------|----|---------------------|---------------------|
| ![Chemical Structure](image3) | C⁴a-C⁸a-S-C₂ = 18.1 | C⁸a-S-C₂-C(H) = 160.5 |
| | S-C₂-C(H)-C₁' = -4.8 | C₂-C(H)-C₁'-C₂' = 3.6 |
| | C₂'-C₃'-O-C(H₃) = -115.1 | |
| Z, c1.4 | ![Chemical Structure](image1) | \( C_1 \) | -1258.648565 (0.2) | -1258.426148 (0.0) |
|----------|-----------------|-----------------|----------------|-----------------|
|          | C4a-C8a-S-C2 = 16.8 | C8a-S-C2-C(H) = 161.9 | S-C2-C(H)-C1' = -3.8 | C2-C(H)-C1'-C2' = -174.0 |
|          | S-C2 = 16.8 | C8a-S-C2 = 16.8 | S-C2-C(H)-C1' = -3.8 | C2-C(H)-C1'-C2' = -174.0 |
|          | C2-S2 = -1258.648565 (0.2) | -1258.426148 (0.0) | 1258.648565 (0.2) | -1258.426148 (0.0) |
| Z, c1.5 | ![Chemical Structure](image2) | \( C_2 \) | -1258.646371 (1.6) | -1258.425346 (0.5) |
|          | C4a-C8a-S-C2 = 17.6 | C8a-S-C2-C(H) = 160.8 | S-C2-C(H)-C1' = -4.5 | C2-C(H)-C1'-C2' = -174.3 |
|          | S-C2 = 17.6 | C8a-S-C2 = 17.6 | S-C2-C(H)-C1' = -4.5 | C2-C(H)-C1'-C2' = -174.3 |
|          | C2-S2 = -1258.646371 (1.6) | -1258.425346 (0.5) | 1258.646371 (1.6) | -1258.425346 (0.5) |
| Z, c1.6 | ![Chemical Structure](image3) | \( C_2 \) | -1258.646369 (1.6) | -1258.424262 (1.2) |
|          | C4a-C8a-S-C2 = 16.1 | C8a-S-C2-C(H) = 162.8 | S-C2-C(H)-C1' = -4.2 | C2-C(H)-C1'-C2' = -176.1 |
|          | S-C2 = 16.1 | C8a-S-C2 = 16.1 | S-C2-C(H)-C1' = -4.2 | C2-C(H)-C1'-C2' = -176.1 |
|          | C2-S2 = -1258.646369 (1.6) | -1258.424262 (1.2) | 1258.646369 (1.6) | -1258.424262 (1.2) |
Table 4.2. 3-Methylbenzothiazine: electronic transitions [TD-PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)] for the most stable structures identified, and isodensity maps (0.04 a.u.) of selected molecular orbitals

| Isomer / conformer | Schematic drawing | Transition wavelength / nm (oscillator strength): orbitalic contribution (expansion coefficient)³ |
|--------------------|-------------------|------------------------------------------------------------------------------------------------|
| *Z*, c1.1          | ![Schematic](image) | 421.1 (0.41): 78 → 79 (0.69); 78 → 80 (-0.11)  
318.9 (0.32): 76 → 79 (0.19); 78 → 79 (0.10); 78 → 80 (0.66)  
306.4 (0.12): 74 → 79 (0.11); 75 → 79 (0.14); 76 → 79 (-0.23); 77 → 79 (0.60); 78 → 81 (0.16)  
302.7 (0.06): 74 → 79 (0.39); 75 → 79 (0.11); 76 → 79 (-0.38); 77 → 79 (-0.32); 78 → 80 (0.14); 78 → 81 (0.23) |

³ orbitalic contribution: orbitalic contribution (expansion coefficient) in a.u.
Monoprotonated (iminium) form in methanol

(isodensity level 0.016 a.u.)
$Z, c1.1$

![Chemical structure](image)

| 530.5 (0.39): 78 → 79 (0.69) |
|-----------------------------|
| 381.1 (0.08): 77 → 79 (0.69) |
| 344.2 (0.09): 76 → 79 (0.64); 78 → 80 (0.24) |
| 319.7 (0.60): 76 → 79 (-0.23); 78 → 79 (-0.11); **78 → 80 (0.64)** |
| 307.5 (0.08): 75 → 79 (0.65); 78 → 81 (0.21) |

#74, HOMO-4 (-0.32365)  #75, HOMO-3 (-0.29293)  #76, HOMO-2 (-0.28172)  #77, HOMO-1 (-0.26583)  #78, HOMO (-0.22808)
| #79, LUMO (-0.12022) | #80, LUMO+1 (-0.05489) | #81, LUMO+2 (-0.04101) | #82, LUMO+3 (-0.02046) | #83, LUMO+4 (-0.00896) |
|----------------------|------------------------|------------------------|------------------------|------------------------|
| (isodensity level 0.016 a.u.) |

**Monoanionic (phenate) form in methanol**

| Reaction | Energy (kcal/mol) | Product | Reaction | Energy (kcal/mol) | Product |
|----------|-------------------|---------|----------|-------------------|---------|
| 78 → 79 | 507.4 (0.51) | 79 | 78 → 80 | 365.4 (0.38) | 78 | 78 → 80 (0.68) |
| 78 → 81 | 346.5 (0.14) | 81 | 76 → 79 (0.17) | 328.6 (0.08) | 77 → 79 (0.66) |
| 76 → 80 (0.12) | 321.1 (0.01) | 76 → 81 (0.12) | 77 → 79 (-0.17) |
| 76 → 83 (0.16) | 319.5 (0.01) | 76 → 84 (-0.13) |
| 78 → 82 (0.66) | 301.0 (0.14) | 78 → 85 (0.35) |
#74, HOMO-4 (-0.25375)

#75, HOMO-3 (-0.24029)

#76, HOMO-2 (-0.23445)

#77, HOMO-1 (-0.22423)

#78, HOMO (-0.16892)

#79, LUMO (-0.05939)

#80, LUMO+1 (-0.01817)

#81, LUMO+2 (-0.01320)

#82, LUMO+3 (0.00162)

#83, LUMO+4 (0.00865)

[a] Only transitions above 300 nm are reported. Transitions with $f > 0.1$ are highlighted, along with their main orbitalic contributions.

[b] Orbital energies in hartrees.
Figure 4.1. 3-Methylbenzothiazine: plot of selected orbital energies [PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)]

Figure 4.2. 3-Methylbenzothiazine: TD-PBE0 calculations
Figure 4.3. 3-Methylbenzothiazine: TD-M06-2X calculations
vanillin, 3-methylbenzothiazine
monoprotonated (iminium) form in methanol

vanillin, 3-methylbenzothiazine
monosodium (phenate) form in methanol
Part 5. Comparisons

Figure 5.1. Plot of frontier orbital energies [PBE0 / 6-311++G(2d,2p) // PBE0 / 6-31+G(d,p)] of different cyanines as a function of protonation state.
Spectrophotometric coding/decoding:
flow chart:

a) Preparing the code generating sets A and B;
b) Sending the message (encryption with public key);
c) Decoding the message (decryption with private key)
Preparing the code generating sets A and B.

Step 1: recording UV-visible spectra of the 8 compounds at acidic and alkaline pH

1 = 1a; 2 = 2°a; 3 = 3a; 4 = 4a;
5 = 1b; 6 = 2b; 7 = 3b; 8 = 4b
a) Preparing the code generating sets A and B.
Step 2: determining the $A_{H^+}/A_{OH^-}$ ratio spectra and shifting abscissa axis values.

EXAMPLES...
a) Preparing the code generating sets A and B.

Step 3: preparing mixtures for each set.

Example: preparing mixtures by mixing compounds 1-4 a/b at specific molar ratios, defined below by coefficients A-H:

\[ A^1 + B^2 + C^3 + D^4 + E^5 + F^6 + G^7 + H^8: \{0 \leq A, B, ..., H \leq 100\} \]

Mixture n

\[ 11^1 2^2 6^3 2^4 2^5 2^6 2^7 2^8 \]

Mixture m

\[ 1^1 8^2 0^3 25^4 8^5 0^6 0^7 0^8 \]

UV plots of mixtures m and n at acidic and alkaline pH

ratio spectra and abscissa shifting
a) Preparing the code generating sets A and B.

Step 4: definition of sets

- Select two separate abscissa intervals (I and II) for ratio spectra of mixtures m and n
- Obtain definite integrals for intervals I and II
- Assign mixtures to either of set A or B based on I/II integral ratio

Definite integration for intervals I and II

\[
\begin{align*}
\text{I / II integral ratio} \\
< K/(I+II) & \quad \text{then set “A”} \\
\geq K/(I+II) & \quad \text{then set “B”} \\
\end{align*}
\]

else: exclude
a) Preparing the code generating sets A and B.

*Step 5: preparing mixtures for each set*

\[ s = m + n \]

12 10 6 27 10 2 2 2

Alkaline and acid UV plots

finite integration over intervals I and II

\[ \frac{I}{II} \text{ integral ratio} \]

\[ < x \text{ then read ”1”} \]

\[ > x \text{ and } < y \text{ then read ”0”} \]

\[ > y \text{ then read ”1”} \]
**b) Sending the message (encryption with public key)**

*Step 1: mixing components from 5-element sets to generate code.*

Five elements set (example)

|   | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| a1| 1 | 1 | 5 | 1 | 1 | 1 | 1 | 1 |
| a2| 1 | 1 | 2 | 5 | 1 | 1 | 5 | 1 |
| a3| 2 | 1 | 10| 5 | 1 | 1 | 1 | 1 |
| a4| 6 | 1 | 5 | 1 | 5 | 0 | 1 | 0 |
| a5| 7 | 1 | 2 | 1 | 1 | 1 | 0 | 1 |

**A set**

|   |
|---|
| 1 |

|   |
|---|
| 0 |

**B set**

|   |
|---|
| 1 |

“1” => $a_i + a_j$ or $b_i + b_j$ for any $i, j \{1-5\} \cup i\neq j$

“0” => $a_i + b_j$ for any $i, j \{1-5\}$
### a,a generated code digits

| ai  | composition | ratio       | Code digit |
|-----|-------------|-------------|------------|
| a1  | 2 2 10 2 2 2 2 2 2 2 19.904397 1
|     | 2 2 7 6 2 2 2 6 2 14.532848 1
|     | 3 2 15 6 2 2 2 2 2 21.083312 1
|     | 7 2 10 2 6 1 2 1 22.945034 1
|     | 8 2 7 2 2 2 2 1 23.464458 1
| a2  | 2 2 4 10 2 2 2 10 2 24.979902 1
|     | 3 2 12 10 2 2 2 6 2 14.280771 1
|     | 7 2 7 6 6 1 6 1 19.73684 1
|     | 8 2 4 6 2 2 2 5 24.062907 1
| a3  | 4 2 20 10 2 2 2 2 2 21.242674 1
|     | 8 2 15 6 6 1 2 1 23.878074 1
|     | 9 2 12 6 2 2 2 1 24.976333 1
| a4  | 12 2 10 2 10 0 2 0 20.161042 1
|     | 13 2 7 2 6 1 1 1 20.109847 1
| a5  | 14 2 4 2 2 2 2 0 18.100851 1

---

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## b,b generated code digits

| bi  | composition | ratio  | Code digit |
|-----|-------------|--------|------------|
| b1  |             |        |            |
| 0   | 10          | 2      | 20         | 0          | 0          | 0          | 0          | 2 54.425585 | 1 |
| 0   | 105         | 2      | 10         | 1          | 0          | 0          | 0          | 1 39.598706 | 1 |
| 1   | 13          | 1      | 35         | 8          | 0          | 0          | 1          | 1 51.973182 | 1 |
| 0   | 13          | 2      | 11         | 1          | 1          | 1          | 1          | 6 58.012962 | 1 |
| 1   | 6           | 2      | 15         | 1          | 5          | 1          | 6          | 1 53.963453 | 1 |
| b2  |             |        |            |
| 0   | 200         | 2      | 0          | 2          | 0          | 0          | 0          | 0 40.889027 | 1 |
| 1   | 108         | 1      | 25         | 9          | 0          | 0          | 0          | 0 58.399391 | 1 |
| 0   | 108         | 2      | 1          | 2          | 1          | 1          | 1          | 5 85.066428 | 1 |
| 1   | 101         | 2      | 5          | 2          | 5          | 1          | 5          | 1 91.890966 | 1 |
| b3  |             |        |            |
| 2   | 16          | 0      | 50         | 16         | 0          | 0          | 0          | 0 53.736068 | 1 |
| 1   | 16          | 1      | 26         | 9          | 1          | 1          | 1          | 5 62.90136  | 1 |
| 2   | 9           | 1      | 30         | 9          | 5          | 1          | 5          | 5 62.908166 | 1 |
| b4  |             |        |            |
| 0   | 16          | 2      | 2          | 2          | 2          | 2          | 10         | 53.189214  | 1 |
| 1   | 9           | 2      | 6          | 2          | 6          | 2          | 10         | 1 50.116119 | 1 |
| b5  |             |        |            |
| 2   | 2           | 2      | 10         | 2          | 10         | 2          | 10         | 1 41.278287 | 1 |
### a,b generated code digits

| $bi$ | composition | ratio  | Code digit |
|------|-------------|--------|------------|
| a1B  | 1 6 6 11 1 1 1 1 2 35.436792 0 |
|      | 1 101 6 1 2 1 1 1 36.404819 0 |
|      | 2 9 5 26 9 1 1 1 40.960213 1 |
|      | 1 9 6 2 2 2 2 6 41.119423 1 |
|      | 2 2 6 6 2 6 2 6 35.872411 0 |
| a2B  | 1 6 3 15 1 1 5 2 38.318508 0 |
|      | 1 101 3 5 2 1 5 1 37.036935 0 |
|      | 2 9 2 30 9 1 5 1 42.968637 1 |
|      | 1 9 3 6 2 2 6 6 43.621538 1 |
|      | 2 2 3 10 2 6 6 6 38.786055 0 |
| a3B  | 2 6 11 15 1 1 1 2 30.409679 0 |
|      | 2 101 11 5 2 1 1 1 33.748541 0 |
|      | 3 9 10 30 9 1 1 1 36.363951 0 |
|      | 2 9 11 6 2 2 2 6 37.155339 0 |
|      | 3 2 11 10 2 6 2 6 34.015815 0 |
| a4B  | 6 6 6 11 5 0 1 1 30.226821 0 |
|      | 6 101 6 1 6 0 1 0 34.739289 0 |
|      | 7 9 5 26 13 0 1 0 36.7149 0 |
|      | 6 9 6 2 6 1 2 5 36.214427 0 |
|      | 7 2 6 6 6 5 2 5 31.617977 0 |
| a5B  | 7 6 3 11 1 1 0 2 31.616622 0 |
|      | 7 101 3 1 2 1 0 1 35.585314 0 |
|      | 8 9 2 26 9 1 0 1 37.813604 0 |
|      | 7 9 3 2 2 2 1 6 36.899259 0 |
|      | 8 2 3 6 2 6 1 6 31.371633 0 |
