

All data taken at the Pacific Northwest National Laboratory

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Data Analysis: Tracy J. Baker

**Composite spectrum for:** Methyl paraoxon

- First Column: Position in wavenumber ( $\text{cm}^{-1}$ )
- Second column: Real refractive index  $n(\tilde{\nu})$  (dispersion index)
- Third column: Imaginary refractive index,  $k(\tilde{\nu})$  (absorption index per unit length in centimeters)

Where the complex refractive index  $\hat{n} = n(\tilde{\nu}) + ik(\tilde{\nu})$

Following Bertie (in the references below) we define the absorbance as  $A = -\log_{10}(I/I_0)$  and the linear absorption coefficient  $K = A/d$ , where  $d$  is the path length. The connection between the imaginary refractive index and the absorbance coefficient arises from the following:  $2.303K = 4\pi\tilde{\nu}k$

See the following references for a detailed description of terms and units:

- 1) Bertie, J. E., Zhang, S. L., Eysel, H. H., Baluja, S., & Ahmed, M. K. (1993). Infrared Intensities of Liquids XI: Infrared Refractive Indices from 8000 to  $2\text{ cm}^{-1}$ , Absolute Integrated Intensities, and Dipole Moment Derivatives of Methanol at  $25^\circ\text{C}$ . *Appl. Spec.*, 47(8), 1100-1114 doi:10.1366/0003702934067973
- 2) Bertie, J. E., Zhang, S. L., & Keefe, C. D. (1995). Measurement and use of absolute infrared absorption intensities of neat liquids. *Vibrational Spectroscopy*, 8(2), 215-229. doi:10.1016/0924-2031(94)00038-i

**Sample:**

- Chemical name, formula and CAS number: Methyl paraoxon,  $\text{C}_8\text{H}_{10}\text{NO}_6\text{P}$ , [950-35-6]
- IUPAC name: Dimethyl (4-nitrophenyl) phosphate
- Synonyms: *O,O*-Dimethyl *O*-(4-nitrophenyl) phosphate; Paraoxon-methyl
- Physical properties: FW = 247.14 g/mole; mp =  $0-4^\circ\text{C}$ ; bp =  $315^\circ\text{C}$ ;  $\rho = 1.383\text{ g/cm}^3$
- Supplier and stated purity: TRC, 99% (Lot # 16-RCD-102-1)
- Temperature of sample:  $25^\circ\text{C}$  ( $\pm 1^\circ\text{C}$ )
- Individual samples were measured at the following path lengths: MIR: 2.27, 2.47, 3.83, 11.6, 19.3, 35.6, 46.6, 91.5, 193 and 495 micrometers ( $\mu\text{m}$ ); NIR: 91.8, 192, 496, 1005 and 2163  $\mu\text{m}$ . Final data are a composite of these spectra.
- Sample cell window material: MIR = potassium bromide (KBr) except potassium chloride (KCl) for the 92.5 and 495  $\mu\text{m}$  cells; NIR = KBr except KCl for the 91.8, 496 and 2163  $\mu\text{m}$  cells.
- Preparation: None

**NIR Instrument Parameters:**

- Bruker Vertex 70, purged with UHP nitrogen
- Spectral range: 10,000 to  $3,000\text{ cm}^{-1}$  (1.0 to 3.33 microns)
- NIR source: Quartz tungsten bulb
- Beamsplitter: Broadband potassium bromide (KBr)
- Detector: DLTGS at room temperature
- Aperture: 3 mm
- Folding limits: 31597.6 to  $0\text{ cm}^{-1}$

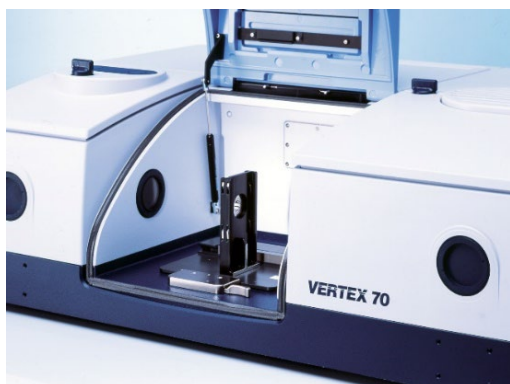
**MIR Instrument Parameters:**

- Tensor II with sample stage rotated 6 degrees, purged with UHP nitrogen
- Spectral range: 7,800 to  $400\text{ cm}^{-1}$  (1.282 to 25 microns)
- IR source: Silicon carbide glow bar
- Beamsplitter: Potassium bromide (KBr)
- Detector: DTGS at room temperature
- Aperture: 3 mm
- Folding limits: 11664.15 to  $0\text{ cm}^{-1}$

### NIR/MIR Instrument Parameters:

- Instrument resolution: 2.0 cm<sup>-1</sup>
- Number of interferograms averaged per single channel spectrum: 128
- Apodization: Norton-Beer, Medium
- Phase correction: Mertz
- Scanner velocity: 10 kHz; 7.5 kHz (MIR)
- Interferogram zerofill: 4x
- Spectral interval after zerofilling: 0.4822 cm<sup>-1</sup>

a)



b)



Figure 1: The Bruker Vertex 70 FTIR (a) and Tensor II (b).

### Measured Refractive Index:

The refractive index for Methyl paraoxon was measured at 25 °C using an Atago model DR-M2/1550 Abbe refractometer. Notch filters were employed in front of a white light source to make measurements at multiple wavelengths. An infrared viewer from Atago was used to detect signal at 1550 nm. The temperature was controlled to match that in the sample compartment of the FTIR using a heated circulating bath.

480 nm: $n = 1.5387$	486 nm: $n = 1.5374$	546 nm: $n = 1.5276$
589 nm: $n = 1.5226$	644 nm: $n = 1.5179$	656 nm: $n = 1.517$
1550 nm: $n = 1.4951$		

The refractive index,  $n$ , vs. wavelength in microns,  $\lambda$ , was fit to an equation similar to that of Sellmeier:

$$n(\lambda) = \{a + b/(\lambda^2 - c)\}^{1/2}$$

The resulting best-fit equation was used to find the refractive index at the highest energy data points in our experimental spectra. For Methyl paraoxon, the results were

$$\begin{aligned} n(7,800 \text{ cm}^{-1}) &= 1.4974 \text{ at } 25 \text{ }^\circ\text{C for MIR data and} \\ n(10,000 \text{ cm}^{-1}) &= 1.5019 \text{ at } 25 \text{ }^\circ\text{C for NIR and merged data.} \end{aligned}$$

### Post Processing and Related Parameters:

For the MIR, a composite spectrum was created from 10 absorbance spectra (base-10) taken at 10 path lengths: 2.27, 2.47, 3.83, 11.6, 19.3, 35.6, 46.6, 91.5, 193 and 495 micrometers ( $\mu\text{m}$ ). These data were collected with the sample stage rotated by  $-6^\circ$  to minimize artifacts resulting from back-reflection into spectrometer (see Johnson et al., *Appl. Spectrosc.*, 76(5) 620-624, 2021). For the NIR, a composite spectrum was created from 5 absorbance spectra (base-10) taken at 5 path lengths: 91.8, 192, 496, 1005 and 2163  $\mu\text{m}$ . The same cells and liquid fills for the  $\sim 100$ , 200 and 500  $\mu\text{m}$  path lengths were used for both spectral ranges. At each path length several spectra were measured and the results averaged for better signal to noise. The measured cell lengths were adjusted using Beer's law plots in which the NIR and MIR data were analyzed independently.

- 1) The imaginary part of the refractive index, or  $k$  vector, was determined for each absorbance file as per Bertie's program "RNJ46A" (see reference above). This takes into account the reflective losses due to the KBr and/or KCl windows.
- 2) A composite  $k$  vector is created via a classical, weighted, linear, least squares fit using the output files of program "RNJ46A": Intercept=0, slope is fitted, individual absorbance values weighted by  $T^2$  (transmission squared), all absorbance values  $\geq 2.5$  are given zero weight. For the MIR, nine composite vectors were created and merged by hand.
  - a) The first  $k$  vector used the results from the 91.5 and 495  $\mu\text{m}$  cells. This  $k$  vector determined the final values for the range from 7800 to 3250  $\text{cm}^{-1}$ .
  - b) The second  $k$  vector used the results from 35.6 through 91.5  $\mu\text{m}$  cells. This  $k$  vector determined the final values for the range from 3250 to 2800  $\text{cm}^{-1}$ .
  - c) The third  $k$  vector used the results from the 495  $\mu\text{m}$  cells. This  $k$  vector determined the final values for the range from 2800 to 1800  $\text{cm}^{-1}$ .
  - d) The fourth  $k$  vector used the results from the 11.6 through 46.6  $\mu\text{m}$  cells. This  $k$  vector determined the final values for the range from 1800 to 1600  $\text{cm}^{-1}$ .
  - e) The fifth  $k$  vector used the results from the 3.83 and 11.6  $\mu\text{m}$  cells. This  $k$  vector determined the final values for the range from 1600 to 1220  $\text{cm}^{-1}$ .
  - f) The sixth  $k$  vector used the results from the 3.83 through 19.3  $\mu\text{m}$  cells. This  $k$  vector determined the final values for the range from 1220 to 850  $\text{cm}^{-1}$ .
  - g) The seventh  $k$  vector used the results from the 11.6 and 19.3  $\mu\text{m}$  cells. This  $k$  vector determined the final values for the range from 850 to 780  $\text{cm}^{-1}$ .
  - h) The eighth  $k$  vector used the results from the 11.6 through 46.6  $\mu\text{m}$  cells. This  $k$  vector determined the final values for the range from 780 to 560  $\text{cm}^{-1}$ .
  - i) The ninth  $k$  vector used the results from the 35.6 and 46.6  $\mu\text{m}$  cells. This  $k$  vector determined the final values for the range from 560 to 370  $\text{cm}^{-1}$ .
- 3) A frequency correction was applied to the resulting composite MIR  $k$  vector.
  - a) Frequency correction (already applied):  $\tilde{\nu}(\text{corrected}) = [\tilde{\nu}(\text{instrument}) * 0.99988 + 0.025]$  as determined by comparing measured atmospheric spectral lines ( $\text{H}_2\text{O}$  and  $\text{CO}_2$ ) to values from the Northwest Infrared Spectral Library Database.
- 4) For the NIR, five composite vectors were created and merged by hand.
  - a) The first  $k$  vector used the results from the 2163  $\mu\text{m}$  cell. This  $k$  vector determined the final values for the range from 10,000 to 4750  $\text{cm}^{-1}$ .
  - b) The second  $k$  vector used the results from the 496 and 1005  $\mu\text{m}$  cells. This  $k$  vector determined the final values for the range from 4750 to 3700  $\text{cm}^{-1}$ .
  - c) The third  $k$  vector used the results from the 91.8 and 496  $\mu\text{m}$  cells. This  $k$  vector determined the final values for the range from 3700 to 3300  $\text{cm}^{-1}$ .
  - d) The fourth  $k$  vector used the results from the 91.8  $\mu\text{m}$  cell. This  $k$  vector determined the final values for the range from 3300 to 2845  $\text{cm}^{-1}$ .
  - e) The fifth  $k$  vector used the results from all the cells. This  $k$  vector determined the final values for the range from 2845 to 370  $\text{cm}^{-1}$ .
- 5) The resulting composite NIR  $k$  vector and the refractive index at 10,000  $\text{cm}^{-1}$  were used to create the real or  $n$  vector using the Kramers-Kronig relation, as per Bertie's program "LZZKTB".
  - a) Frequency correction (already applied):  $\tilde{\nu}(\text{corrected}) = [\tilde{\nu}(\text{instrument}) * 0.99998 - 0.0005]$  as determined by comparing measured atmospheric spectral lines ( $\text{H}_2\text{O}$  and  $\text{CO}_2$ ) to values from the

Northwest Infrared Spectral Library Database.

- 6) The MIR data were mapped onto the NIR x-axis using an interpolation routine, i.e. the Make Compatible command in OPUS 5.5. Then the composite MIR and NIR  $k$  vectors were merged to generate a final composite  $k$  vector across the entire spectral range. The NIR data were used exclusively above  $3383\text{ cm}^{-1}$ , and only the MIR data were used below  $3291\text{ cm}^{-1}$ . A weighted average, with the weight of the MIR vector increasing linearly from 0 to 100% between  $3383$  and  $3291\text{ cm}^{-1}$ , was used in the overlapping spectral region. The resulting composite  $k$  vector and the refractive index at  $10,000\text{ cm}^{-1}$  were used to create the final  $n$  vector using the Kramers-Kronig relation, as per Bertie's program "LZZKTB."

#### Photograph of Sample Methyl paraoxon:



Figure 2: Methyl paraoxon in TRC container for NIR and MIR measurements.