

All data taken at the Pacific Northwest National Laboratory

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Composite spectrum for: (+)- β -Pinene

- First Column: Position in wavenumber (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 cm^{-1} , Absolute Integrated Intensities, and Dipole Moment Derivatives of Methanol at 25°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: (+)- β -Pinene, $\text{C}_{10}\text{H}_{16}$, [19902-08-0]
- IUPAC name: (1R,5R)-6,6-Dimethyl-4-methylenebicyclo[3.1.1]heptane
- Synonyms: (+)-beta-Pinene; (1R,5R)-2(10)-Pinene; D- β -Pinene
- Physical properties: FW = 136.23 g/mole; mp = -61.5°C ; bp = $164\text{--}165^\circ\text{C}$; $\rho = 0.872\text{ g/cm}^3$
- Supplier and stated purity: Sigma Aldrich, $\geq 98.5\%$ (Lot # BCBW1470)
- Temperature of sample: 26°C ($\pm 1^\circ\text{C}$)
- Individual samples were measured at the following path lengths: MIR: 3.10, 8.11, 8.51, 19.8, 40.3, 66.6, 120, 205 and $512\text{ }\mu\text{m}$; NIR: 121, 204, 512, 1005 and $3089\text{ }\mu\text{m}$. Final data are a composite of these spectra.
- Sample cell window material is potassium bromide (KBr) except for the 3.10, 40.3, 512 and $1005\text{ }\mu\text{m}$ cells, which are potassium chloride (KCl).
- Preparation: None.

NIR Instrument Parameters:

- Bruker Vertex 70, purged with UHP nitrogen
- Spectral range: $10,000\text{ to }3,000\text{ cm}^{-1}$ (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: $31601\text{ to }0\text{ cm}^{-1}$

MIR Instrument Parameters:

- Tensor 27, purged with UHP nitrogen
- Spectral range: $7800\text{ to }400\text{ cm}^{-1}$ (1.282 to 25 microns)
- IR source: Silicon carbide glow bar
- Beamsplitter: Broadband Potassium bromide (KBr)
- Detector: DLTGS at room temperature
- Aperture: 3 mm
- Folding limits: $15801\text{ to }0\text{ cm}^{-1}$

NIR/MIR Instrument Parameters:

- Instrument resolution: 2.0 cm^{-1}
- Number of interferograms averaged per single channel spectrum: 128
- Apodization: Norton-Beer, Medium
- Phase correction: Mertz
- Scanner velocity: 10 kHz
- Interferogram zerofill: 4x
- Spectral interval after zerofilling: 0.4823 cm^{-1}

a)



b)



Figure 1: The Bruker Vertex 70 FTIR (a) and Tensor 27 FTIR (b).

Measured Refractive Index:

The refractive index for (+)- β -Pinene was measured at $25\text{ }^{\circ}\text{C}$ 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: $n = 1.4828$	486 nm: $n = 1.4825$	546 nm: $n = 1.4781$
589 nm: $n = 1.4751$	644 nm: $n = 1.4731$	656 nm: $n = 1.4728$
1550 nm: $n = 1.4515$		

The refractive index, n , vs. wavelength in microns, λ , 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 (+)- β -Pinene, the results were

$$\begin{aligned} n(7800\text{ cm}^{-1}) &= 1.4546 \text{ at } 25\text{ }^{\circ}\text{C} \text{ for MIR data and} \\ n(10,000\text{ cm}^{-1}) &= 1.4599 \text{ at } 25\text{ }^{\circ}\text{C} \text{ for NIR and merged data.} \end{aligned}$$

Post Processing and Related Parameters:

For the MIR, a composite spectrum was created from 9 absorbance spectra (base-10) taken at 9 path lengths: 3.10, 8.11, 8.51, 19.8, 40.3, 66.6, 120, 205 and 512 micrometers (μm). For the NIR, a composite spectrum was created from 5 absorbance spectra (base-10) taken at 5 path lengths: 121, 204, 512, 1005 and 3089 μm . The same cells for the ~100, 200 and 500 μm 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 windows and the measured refractive index at 7800 cm^{-1} for the MIR data and 10,000 cm^{-1} for the NIR data.
- 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 ≥ 2.5 are given zero weight. For the MIR, eight composite vectors were created and merged by hand.
 - a) The first k vector used the results from the 119.8 and 204.8 μm cells. This k vector determined the final values for the range from 7800 to 6704 cm^{-1} .
 - b) The second k vector used the results from the 205 and 512 μm cells. This k vector determined the final values for the range from 6704 to 4914 cm^{-1} .
 - c) The third k vector used the results from the 40.3 and 66.6 μm cells. This k vector determined the final values for the range from 4914 to 3011 cm^{-1} .
 - d) The fourth k vector used the results from the 3.10, 8.11, and 8.51 μm cells. This k vector determined the final values for the range from 3011 to 2733 cm^{-1} .
 - e) The fifth k vector used the results from the 19.8, 40.3, and 66.6 μm cells. This k vector determined the final values for the range from 2733 to 1483 cm^{-1} .
 - f) The sixth k vector used the results from the 8.11, 8.51, 19.8, 40.3, and 66.6 μm cells. This k vector determined the final values for the range from 1483 to 921 cm^{-1} .
 - g) The seventh k vector used the results from the 8.11, 8.51, 19.8, and 40.3 μm cells. This k vector determined the final values for the range from 921 to 635 cm^{-1} .
 - h) The eighth k vector used the results from the 66.6, 120, and 205 μm cells. This k vector determined the final values for the range from 635 to 400 cm^{-1} .
- 3) A frequency correction was applied to the resulting composite MIR k vector.
 - a) Frequency correction (already applied): $\tilde{\nu}(\text{corrected}) = [\tilde{\nu}(\text{instrument}) * .999848 + .010722]$ as determined by comparing measured atmospheric spectral lines (H_2O and 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 512 and 1005 μm cells. This k vector determined the final values for the range from 10000 to 9080 cm^{-1} .
 - b) The second k vector used the results from the 512, 1005 and 3089 μm cells. This k vector determined the final values for the range from 9080 to 7587 cm^{-1} .
 - c) The third k vector used the results from the 121, 204, 512, 1005 and 3089 μm cells. This k vector determined the final values for the range from 7587 to 6268 cm^{-1} .
 - d) The fourth k vector used the results from the 204, 512, 1005 and 3089 μm cells. This k vector determined the final values for the range from 6268 to 5550 cm^{-1} .
 - e) The fifth k vector used the results from the 121, 204, 512 and 1005 μm cells. This k vector determined the final values for the range from 5550 to 3000 cm^{-1} .
- 5) A frequency correction was applied to the resulting composite NIR k vector.
 - a) Frequency correction (already applied): $\tilde{\nu}(\text{corrected}) = [\tilde{\nu}(\text{instrument}) * .999869 + .0158818]$ as determined by comparing measured atmospheric spectral lines (H_2O and CO_2) to values from the Northwest Infrared Spectral Library Database.
- 6) Finally, 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

5074 cm^{-1} , and only the MIR data were used below 4819 cm^{-1} . A weighted average, with the weight of the MIR vector increasing linearly from 0 to 100% between 5074 and 4819 cm^{-1} was used in the overlapping spectral region. The resulting composite k vector and the refractive index at 10,000 cm^{-1} were used to create the final n vector using the Kramers-Kronig relation, as per Bertie's program "LZZKTB."

Photograph of Sample (+)- β -Pinene:



Figure 2: (+)- β -Pinene in Sigma Aldrich container.