

# IR + Raman - IR- and Raman-Spectroscopy

Protocol for the PC 2 lab course by  
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**Abstract:**

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# **1 Theory**

## **1.1 IR-Spectroscopy**

## **1.2 Raman-Spectroscopy**

## **1.3 DFT-Calculations**

[1]

## 2 Procedure

To simulate and calculate the vibrational normal modes, the program **Avogadro2** was used. The structures of the molecules methane, chloromethane, dichloromethane, dibromomethane, chloroform, deuterated chloroform, tetrachloromethane and tetrachloroethylene were built, their geometry was optimized and the optimized coordinates were used to calculate the vibrational modes with the **ORCA** software, resulting in a list of IR and Raman frequencies and intensities for each molecule.

In the experimental part, the Raman spectra of dichloromethane, dibromomethane, chloroform, deuterated chloroform, tetrachloromethane and tetrachloroethylene were measured and analyzed with the **WPenlighten** software. The IR spectra of dichloromethane, dibromomethane, chloroform and tetrachloroethylene were measured using an ATR spectrometer and analyzed with the **Opus** software.

## 3 Results and Analysis

### 3.1 Methane

#### 3.1.1 IR

The simulated vibrational modes of methane are summarized in ?? with the corresponding wavenumber, intensity and vibration type of each mode.

Tab. 1: Listed are the simulated wavenumbers and intensities of the IR signals of CH<sub>4</sub> with the corresponding type of the vibrational mode.

Signal	Wavenumber $\tilde{\nu}$ / cm <sup>-1</sup>	Intensity / KM·mol <sup>-1</sup>	Vibration type
1	1313.45	13.30	asym. bending
2	1313.68	13.25	asym. bending
3	1313.73	13.25	asym. bending
4	1530.79	0	sym. bending
5	1531.05	0	sym. bending
6	3019.38	0	sym. stretching
7	3152.03	17.69	asym. stretching
8	3152.33	17.64	asym. stretching
9	3152.45	17.64	asym. stretching

As can be seen in ??, only the asymmetric bending and stretching modes are IR-active, while the symmetric bending and stretching modes are IR-inactive. Furthermore, the asymmetric stretching mode shows the highest wavenumber among the IR-active modes, meaning it requires the most energy to be excited.

### 3.1.2 Raman

The simulated Raman-active vibrational modes of methane are summarized in ?? with the corresponding wavenumber, Raman intensity and vibration type of each mode.

Tab. 2: Listed are the simulated wavenumbers and intensities of the Raman signals of CH<sub>4</sub> with the corresponding type of the vibrational mode.

Mode	Raman shift $\Delta\tilde{\nu}$ / cm <sup>-1</sup>	Raman intensity / Å <sup>4</sup> · amu <sup>-1</sup>	Vibration type
1	1313.38	1.64419	asym. bending
2	1313.61	1.6422	asym. bending
3	1314.1	1.6484	asym. bending
4	1531.00	27.4565	sym. bending
5	1531.09	27.449	sym. bending
6	3019.41	145.177	sym. stretching
7	3150.24	62.8181	asym. stretching
8	3150.27	62.8724	asym. stretching
9	3150.79	62.8305	asym. stretching

In contrast to the IR spectrum, both the symmetric bending and stretching modes are Raman-active. The symmetric stretching mode shows the highest Raman intensity among all vibrational modes, indicating that it is most prominent mode to be observed in a Raman spectrum.

## 3.2 Chloromethane

### 3.2.1 IR

The simulated vibrational modes of methane are summarized in ?? with the corresponding wavenumber, intensity and vibration type of each mode.

Tab. 3: Listed are the simulated wavenumbers and intensities of the vibrational modes of  $\text{CH}_3\text{Cl}$ .

Mode	Wavenumber $\tilde{\nu}$ / $\text{cm}^{-1}$	Intensity / $\text{km mol}^{-1}$	vibration type
1	725.98	23.93	C–Cl stretch
2	1010.21	3.13	rocking
3	1010.42	3.11	rocking
4	1361.61	14.72	scissoring
5	1455.99	6.46	twisting
6	1456.14	6.47	twisting
7	3057.12	21.81	sym. stretching
8	3170.28	6.28	asym. stretching
9	3170.74	6.27	asym. stretching

The table shows that all types of vibrations are IR active but the C–Cl stretching mode as well as the scissoring mode and symmetrical stretching mode are the most intense ones.

### 3.2.2 Raman

The simulated Raman-active vibrational modes of methane are summarized in ?? with the corresponding wavenumber, Raman intensity and vibration type of each mode.

Tab. 4: Listed are the simulated Raman shifts and intensities of the vibrational modes of  $\text{CH}_3\text{Cl}$ .

Mode	Raman Shift $\Delta\tilde{\nu}$ / $\text{cm}^{-1}$	Raman intensity / $\text{\AA}^4 \text{amu}^{-1}$	vibration type
1	725.96	12.69	C–Cl stretch
2	1008.86	6.56	rocking
3	1010.02	6.53	rocking
4	1361.35	3.48	scissoring
5	1455.81	16.49	twisting
6	1456.34	16.50	twisting
7	3056.94	134.62	sym. stretching
8	3169.78	66.78	asym. stretching
9	3170.01	66.72	asym. stretching

The comparison to the IR table shows that all vibrational modes are also raman active but the most intense ones are now the stretching modes, with the symmetrical stretching being the most prominent one.

### 3.3 Dichloromethane

#### 3.3.1 IR

The measured IR spectrum of dichloromethane is shown in ??, plotting the intensity of the absorption against the wavenumber  $\tilde{\nu}$ .

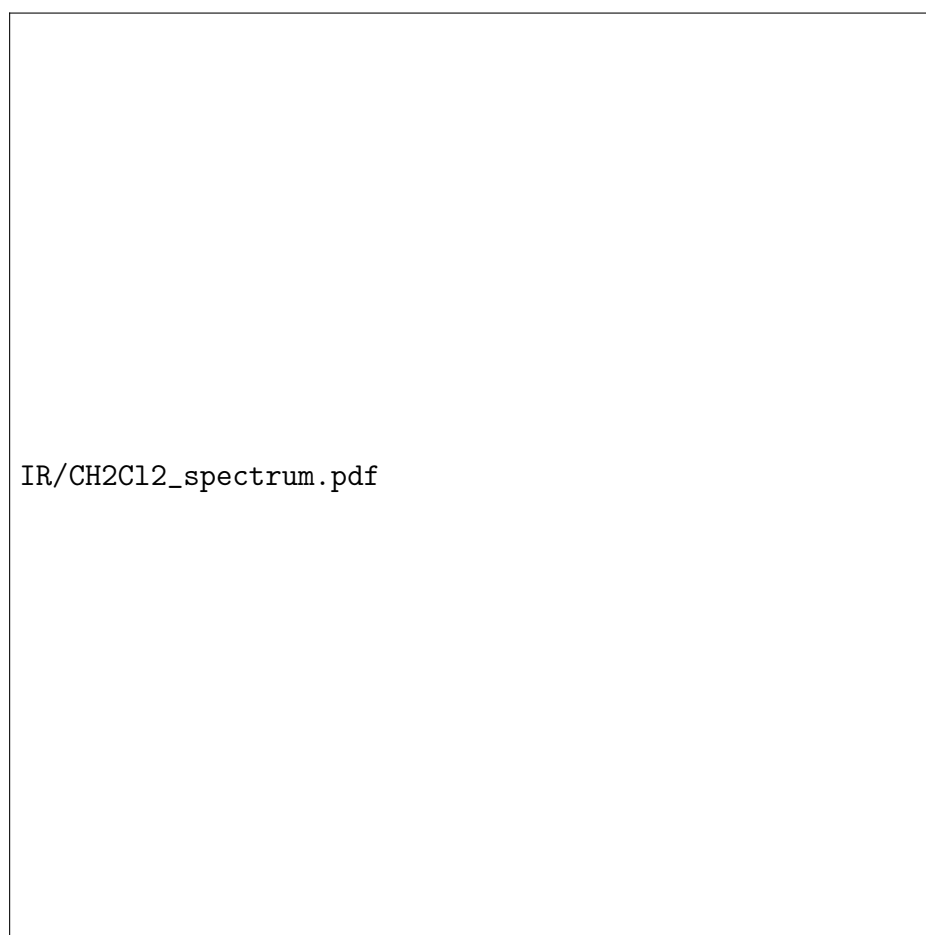


Fig. 1: Measured IR spectrum of dichloromethane.

By visual inspection of the IR spectrum in ??, five absorption signals can be identified, which are listed with their corresponding wavenumbers and intensities in ??.

Tab. 5: Listed are the measured wavenumbers and intensities of the IR signals of  $\text{CH}_2\text{Cl}_2$  with the corresponding type of the vibrational mode.

Signal	Wavenumber $\tilde{\nu}$ / $\text{cm}^{-1}$	Intensity / a.u.	Vibration type
1	704.00	0.45	sym. stretching
2	730.53	1.01	asym. stretching
3	895.82	0.04	rocking
4	1265.17	0.29	wagging
5	1422.29	0.02	scissoring

The simulated vibrational modes of dichloromethane are summarized in ?? with the corresponding wavenumber, intensity and vibration type of each mode.

Tab. 6: Listed are the simulated wavenumbers and intensities of the IR signals of  $\text{CH}_2\text{Cl}_2$  with the corresponding type of the vibrational mode.

Mode	Wavenumber $\tilde{\nu}$ / $\text{cm}^{-1}$	Intensity / $\text{KM}\cdot\text{mol}^{-1}$	Vibration type
1	277.23	0.64	-
2	703.86	14.19	sym. stretching
3	733.80	137.83	asym. stretching
4	889.17	1.20	rocking
5	1153.54	0.00	-
6	1272.86	41.21	wagging
7	1441.46	0.01	scissoring
8	3107.43	9.81	sym. stretching
9	3194.30	0.64	asym. stretching

As can be seen in ??, the most intense IR-active modes are found at wavenumbers of  $733.80 \text{ cm}^{-1}$  and  $1272.86 \text{ cm}^{-1}$ , which correspond well to the measured signals at  $730.53 \text{ cm}^{-1}$  for the asymmetric stretching mode and  $1265.17 \text{ cm}^{-1}$  for the wagging mode in ?. The C-H stretching modes at around  $3100 \text{ cm}^{-1}$  calculated by ORCA are barely visible in ??.

### 3.3.2 Raman

The measured Raman spectrum of dichloromethane is shown in ??, plotting the Raman intensity against the Raman shift  $\Delta\tilde{\nu}$ .



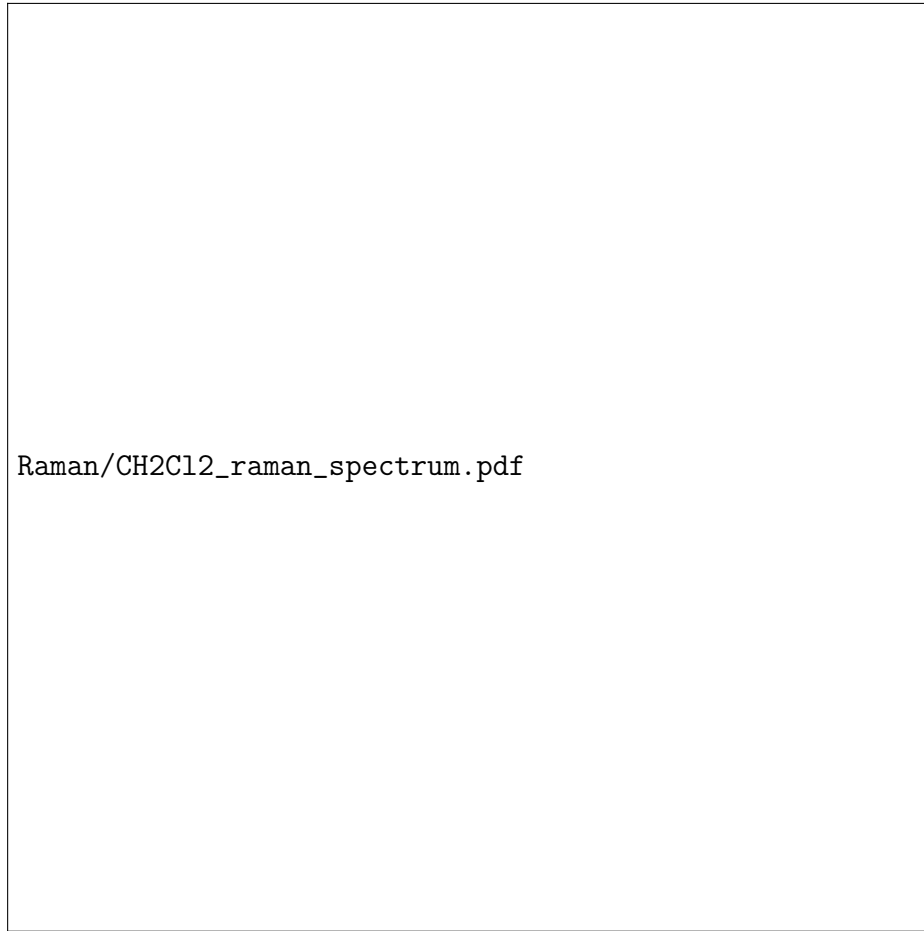


Fig. 2: Measured raman spectrum of dichloromethane.

By visual inspection of the Raman spectrum in ??, five primary absorption signals can be identified, which are listed with their corresponding Raman shift, Raman intensity and vibration type of each mode.

Tab. 7: Listed are the measured Raman shifts and intensities of the signals of  $\text{CH}_2\text{Cl}_2$ .

Signal	Raman shift $\Delta\tilde{\nu}$ / $\text{cm}^{-1}$	intensity / a.u.	Vibration type
1	281.99	2542.67	scissoring
2	697.77	4210.67	sym. stretching
3	1418.07	1563.33	scissoring
4	2984.85	5336.00	sym. stretching
5	3051.13	1775.33	asym. stretching

The simulated Raman-active vibrational modes of dichloromethane are summarized in ?? with the corresponding Raman shift, Raman intensity and vibration type of each mode.

Tab. 8: Listed are the simulated Raman shifts and intensities of the vibrational modes of  $\text{CH}_2\text{Cl}_2$ .

Mode	Raman Shift $\Delta\tilde{\nu}$ / $\text{cm}^{-1}$	Raman intensity / $\text{\AA}^4 \text{ amu}^{-1}$	Vibration type
1	277.06	6.83	scissoring
2	703.48	12.27	sym. stretching
3	732.67	5.02	asym. stretching
4	888.90	3.13	-
5	1153.83	11.78	-
6	1272.67	3.01	-
7	1441.64	12.42	scissoring
8	3106.65	108.70	sym. stretching
9	3193.09	62.65	asym. stretching

As can be seen in ??, the most intense Raman-active modes are found at wavenumbers of  $281.99 \text{ cm}^{-1}$ ,  $697.77 \text{ cm}^{-1}$  and  $2984.85 \text{ cm}^{-1}$ , which correspond to the calculated signals at  $277.06 \text{ cm}^{-1}$  for the scissoring mode and  $703.48 \text{ cm}^{-1}$  for the symmetric stretching mode in ?. But similar to the IR spectrum, the wavenumbers of the C-H stretching modes in the measured Raman spectrum at  $2984.85 \text{ cm}^{-1}$  and  $3051.13 \text{ cm}^{-1}$  deviate by approximately  $130 \text{ cm}^{-1}$  from the calculated values of  $3106.65 \text{ cm}^{-1}$  and  $3193.09 \text{ cm}^{-1}$ .

## 3.4 Dibromomethane

### 3.4.1 IR

The measured IR spectrum of dibromomethane is shown in ??, plotting the intensity of the absorption against the wavenumber  $\tilde{\nu}$ .



Fig. 3: Measured IR spectrum of dibromomethane.

By visual inspection of the IR spectrum in ??, six absorption signals can be identified, which are listed with their corresponding wavenumbers and intensities in ??.

Tab. 9: Listed are the measured wavenumbers and intensities of the IR signals of  $\text{CH}_2\text{Br}_2$ .

Signal	Wavenumber $\tilde{\nu}$ / $\text{cm}^{-1}$	Intensity / a.u.	vibration type
1	455.05	0.52	-
2	577.49	0.49	C–Br sym. stretching
3	632.58	0.95	C–Br asym. stretching
4	677.48	0.23	-
5	812.16	0.23	rocking
6	1095.80	0.08	twisting
7	1189.66	0.53	wagging
8	1389.64	0.02	scissoring
11	3064.97	0.05	-

The simulated vibrational modes of dibromomethane are summarized in ?? with the

corresponding wavenumber, intensity and vibration type of each mode.

Tab. 10: Listed are the simulated wavenumbers and intensities of the vibrational modes of  $\text{CH}_2\text{Br}_2$ .

Mode	Wavenumber $\tilde{\nu}$ / $\text{cm}^{-1}$	Intensity / $\text{KM}\cdot\text{mol}^{-1}$	vibration type
1	168.72	0.08	C–Br scissoring
2	573.58	4.08	C–Br sym. stretching
3	628.31	98.95	C–Br asym. stretching
4	806.07	4.64	rocking
5	1101.92	0.00	twisting
6	1205.80	65.32	wagging
7	1412.95	0.00	scissoring
8	3126.16	1.92	sym. stretching
9	3221.84	1.28	asym. stretching

As ?? shows, the most intense IR-active modes are found at wavenumbers of  $628.31 \text{ cm}^{-1}$  and  $1205.80 \text{ cm}^{-1}$ , which correspond well to the measured signals at  $632.58 \text{ cm}^{-1}$  for the C–Br asymmetric stretching mode and at  $1189.66 \text{ cm}^{-1}$  for the wagging mode. The comparison of the two tables also shows that although the twisting mode and scissoring mode should not be IR-active they still show up in the spectrum.

### 3.4.2 Raman

The measured Raman spectrum of dibromomethane is shown in ??, plotting the Raman intensity against the Raman shift  $\Delta\tilde{\nu}$ .

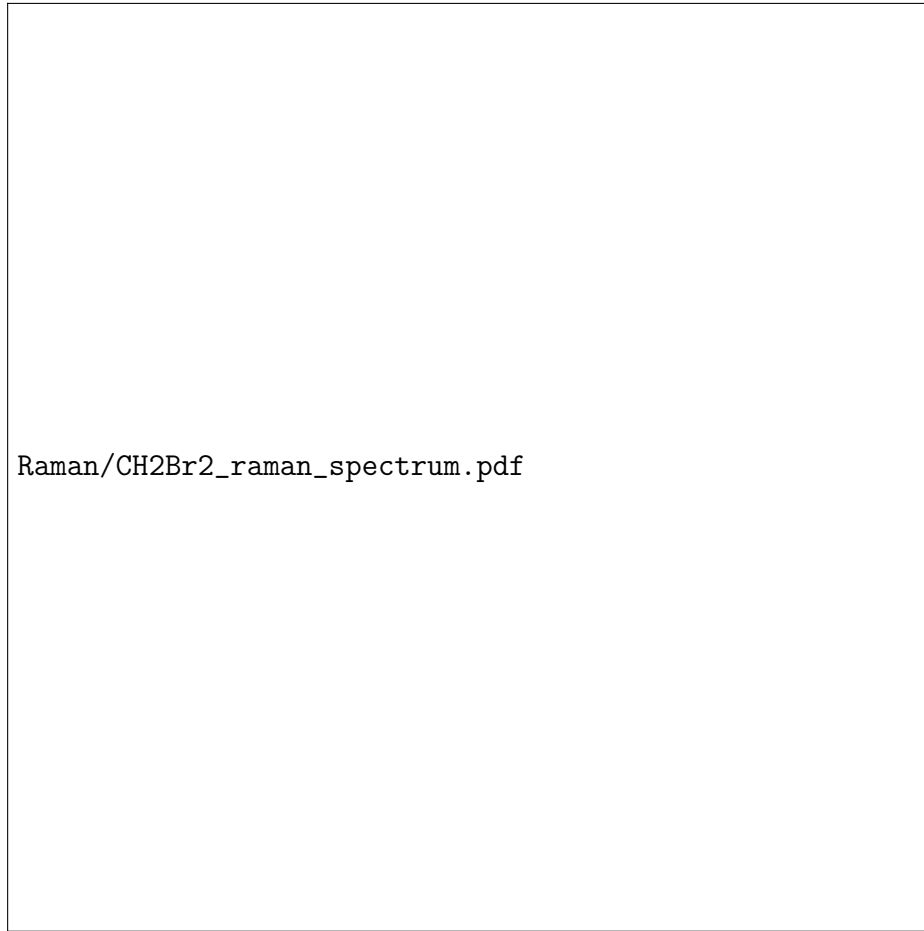


Fig. 4: Measured raman spectrum of dibromomethane.

By visual inspection of the Raman spectrum in ??, seven primary absorption signals can be identified, which are listed with their corresponding Raman shift, Raman intensity and vibration type of each mode.

Tab. 11: Listed are the measured Raman shifts and intensities of the signals of  $\text{CH}_2\text{Br}_2$ .

Signal	Raman shift $\Delta\tilde{\nu}$ / $\text{cm}^{-1}$	Intensity / a.u.	vibration type
1	169.61	4410.67	C–Br scissoring
2	574.79	6711.00	C–Br sym. stretching
3	634.60	2364.33	C–Br asym. stretching
4	1387.16	1889.33	scissoring
5	2432.07	1409.00	-
6	2984.85	5162.00	sym. stretching
7	3062.11	1965.67	asym. stretching

The simulated Raman-active vibrational modes of dibromomethane are summarized in ?? with the corresponding Raman shift, Raman intensity and vibration type of each mode.

Tab. 12: Listed are the simulated wavenumbers and raman intensities of the vibrational modes of  $\text{CH}_2\text{Br}_2$ .

Mode	Wavenumber $\tilde{\nu}$ / $\text{cm}^{-1}$	Raman intensity / $\text{\AA}^4 \text{ amu}^{-1}$	vibration type
1	168.56	5.37	C–Br scissoring
2	574.64	13.43	C–Br sym. stretching
3	629.71	5.36	C–Br asym. stretching
4	806.60	2.41	rocking
5	1102.17	8.43	twisting
6	1205.71	0.74	wagging
7	1413.22	13.77	scissoring
8	3125.63	97.24	sym. stretching
9	3221.31	58.05	asym. stretching

As ?? shows, the most intense Raman-active modes are found at wavenumbers of  $3125.63 \text{ cm}^{-1}$  and  $3221.31 \text{ cm}^{-1}$ , which correspond to the measured signals at  $2984.85 \text{ cm}^{-1}$  for the symmetric stretching mode and at  $3062.11 \text{ cm}^{-1}$  for the asymmetric stretching mode. That means that the symmetric and asymmetric stretching of the C–H bonds is the most Raman-active type of vibration.

## 3.5 Chloroform

### 3.5.1 IR

The measured IR spectrum of chloroform is shown in ??, plotting the intensity of the absorption against the wavenumber  $\tilde{\nu}$ .



Fig. 5: Measured IR spectrum of chloroform.

By visual inspection of the IR spectrum in ??, three absorption signals can be identified, which are listed with their corresponding wavenumbers and intensities in ??.

Tab. 13: Listed are the measured wavenumbers and intensities of the IR signals of  $\text{CHCl}_3$ .

Signal	Wavenumber $\tilde{\nu}$ / $\text{cm}^{-1}$	Intensity / a.u.	vibration type
1	626.46	0.11	-
2	667.27	0.27	C–Cl sym. stretching
3	742.78	1.58	C–Cl asym. stretching
4	910.10	0.03	-
5	928.47	0.02	-
6	1214.15	0.30	bending
7	3020.07	0.02	sym. stretching

The simulated vibrational modes of chloroform are summarized in ?? with the corresponding wavenumber, intensity and vibration type of each mode.

Tab. 14: Listed are the simulated wavenumbers and intensities of the vibrational modes of  $\text{CHCl}_3$ .

Mode	Wavenumber $\tilde{\nu}$ / $\text{cm}^{-1}$	Intensity / $\text{KM}\cdot\text{mol}^{-1}$	vibration type
1	254.78	0.06	C–Cl scissoring
2	254.97	0.06	C–Cl scissoring
3	362.33	0.46	C–Cl scissoring
4	665.85	7.26	C–Cl sym. stretching
5	741.92	167.74	C–Cl asym. stretching
6	742.13	167.67	C–Cl asym. stretching
7	1220.08	22.80	bending
8	1220.17	22.76	bending
9	3169.43	0.22	sym. stretching

As ?? shows, the most intense IR-active modes are found at wavenumbers of  $741.92 \text{ cm}^{-1}$  and  $742.13 \text{ cm}^{-1}$ , which correspond to the measured signal at  $742.78 \text{ cm}^{-1}$  for the C–Cl asymmetric stretching mode. That means that the asymmetric stretching of the C–Cl bond is the most IR active type of vibration. It is to be noted, that the simulation showed two distinct vibrational modes, while the measurement only shows one mode. The simulated bending modes at  $1220.08 \text{ cm}^{-1}$  and  $1220.17 \text{ cm}^{-1}$  that show the second highest intensities, were also measured as only one signal at  $1214.15 \text{ cm}^{-1}$ .

### 3.5.2 Raman

The measured Raman spectrum of chloroform is shown in ??, plotting the Raman intensity against the Raman shift  $\Delta\tilde{\nu}$ .



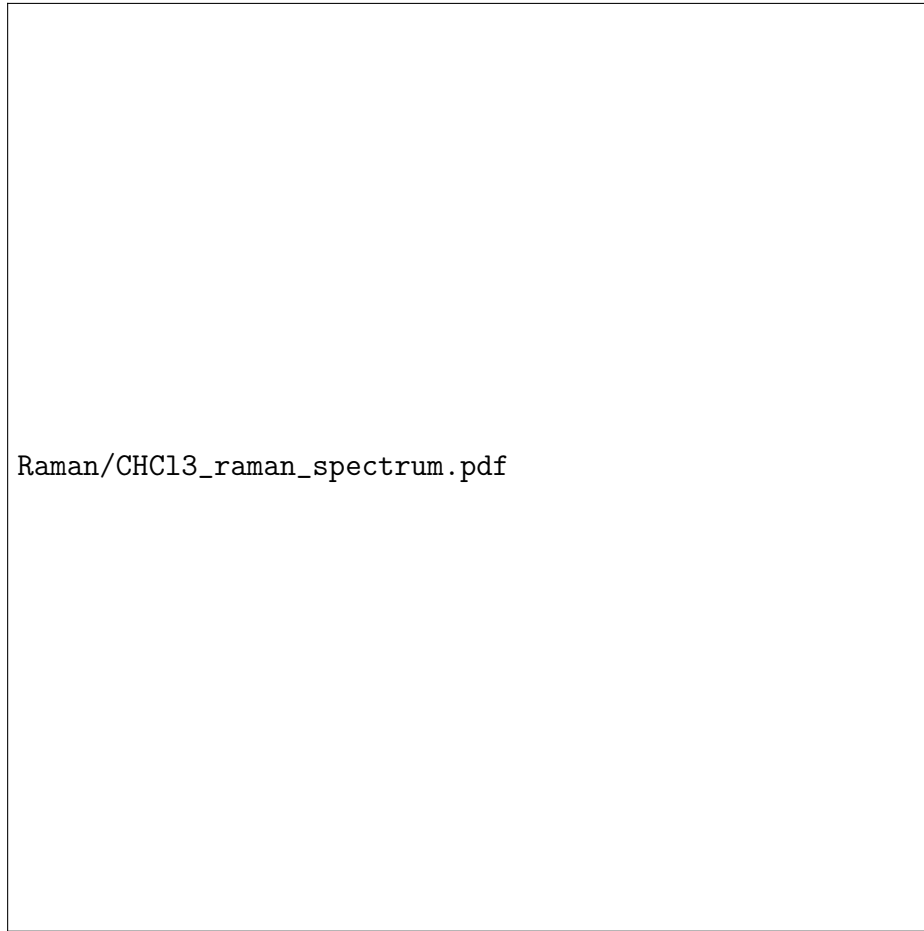


Fig. 6: Measured raman spectrum of chloroform.

By visual inspection of the Raman spectrum in ??, six primary absorption signals can be identified, which are listed with their corresponding Raman shift, Raman intensity and vibration type of each mode.

Tab. 15: Listed are the measured Raman shifts and intensities of the signals of  $\text{CHCl}_3$ .

Signal	Raman shift $\Delta\tilde{\nu}$ / $\text{cm}^{-1}$	Intensity / a.u.	vibration type
1	258.84	2927.00	C–Cl scissoring
2	362.65	3127.33	C–Cl scissoring
3	664.38	3645.00	C–Cl sym. stretching
4	756.86	1811.33	C–Cl asym. stretching
5	1213.44	1437.33	bending
6	3015.32	3161.67	sym. stretching

The simulated Raman-active vibrational modes of tetrachloroethylene are summarized in ?? with the corresponding Raman shift, Raman intensity and vibration type of each mode.

Tab. 16: Listed are the simulated wavenumbers and Raman intensities of the vibrational modes of  $\text{CHCl}_3$ .

Mode	Wavenumber $\tilde{\nu}$ / $\text{cm}^{-1}$	Raman intensity / $\text{\AA}^4 \text{amu}^{-1}$	vibration type
1	254.60	5.14	C–Cl scissoring
2	255.07	5.13	C–Cl scissoring
3	362.22	8.69	C–Cl scissoring
4	665.69	9.80	C–Cl sym. stretching
5	740.88	3.08	C–Cl asym. stretching
6	741.45	3.07	C–Cl asym. stretching
7	1220.22	6.04	bending
8	1220.68	6.05	bending
9	3168.77	77.28	sym. stretching

As ?? shows, the most intense Raman-active mode is found at the wavenumber 3168.77  $\text{cm}^{-1}$ , which corresponds to the measured signal at 3015.32  $\text{cm}^{-1}$  for the symmetric stretching mode. That means that the symmetric stretching of the C–H bond is the most Raman active type of vibration. Even though the C–Cl vibrational modes should not be nearly as intense as the symmetric stretching mode, they almost equal the simulated values.

## 3.6 Deuterated Chloroform

### 3.6.1 IR

Tab. 17: Listed are the simulated wavenumbers and intensities of the vibrational modes of  $\text{CDCl}_3$ .

Mode	Wavenumber $\tilde{\nu}$ / $\text{cm}^{-1}$	Intensity / $\text{KM}\cdot\text{mol}^{-1}$	vibration type
1	253.69	0.06	C–Cl scissoring
2	253.88	0.06	C–Cl scissoring
3	360.12	0.50	C–Cl scissoring
4	646.14	6.66	C–Cl sym. stretching
5	717.83	125.46	C–Cl asym. stretching
6	717.98	125.28	C–Cl asym. stretching
7	909.65	63.16	bending
8	909.66	63.19	bending
9	2342.61	0.74	sym. stretching

## 3.6.2 Raman



Fig. 7: Measured Raman spectrum of deuterated chloroform.

Tab. 18: Listed are the measured Raman shifts and intensities of the signals of  $\text{CDCl}_3$ .

Signal	Raman shift $\Delta\tilde{\nu}$ / $\text{cm}^{-1}$	Intensity / a.u.
1	254.97	2866.67
2	358.83	3009.00
3	645.78	3616.67
4	731.05	1834.67
5	903.05	1434.67
6	2248.93	2796.00

Tab. 19: Listed are the simulated wavenumbers and Raman intensities of the vibrational modes of  $\text{CDCl}_3$ .

Mode	Wavenumber $\tilde{\nu}$ / $\text{cm}^{-1}$	Raman intensity / $\text{\AA}^4 \text{ amu}^{-1}$	vibration type
1	253.69	0.06	C–Cl scissoring
2	253.88	0.06	C–Cl scissoring
3	360.12	0.50	C–Cl scissoring
4	646.14	6.66	C–Cl sym. stretching
5	717.83	125.46	C–Cl asym. stretching
6	717.98	125.28	C–Cl asym. stretching
7	909.65	63.16	bending
8	909.66	63.19	bending
9	2342.61	0.74	sym. stretching

## 3.7 Tetrachloromethane

### 3.7.1 IR

Tab. 20: Listed are the simulated wavenumbers and intensities of the vibrational modes of  $\text{CCl}_4$ .

Mode	Wavenumber $\tilde{\nu}$ / $\text{cm}^{-1}$	Intensity / $\text{KM}\cdot\text{mol}^{-1}$	vibration type
1	212.71	0.00	scissoring
2	212.89	0.00	scissoring
3	310.72	0.06	scissoring
4	310.82	0.06	scissoring
5	310.88	0.06	scissoring
6	451.20	0.00	sym. stretching
7	754.80	185.52	asym. stretching
8	755.02	185.61	asym. stretching
9	755.51	185.58	asym. stretching

## 3.7.2 Raman

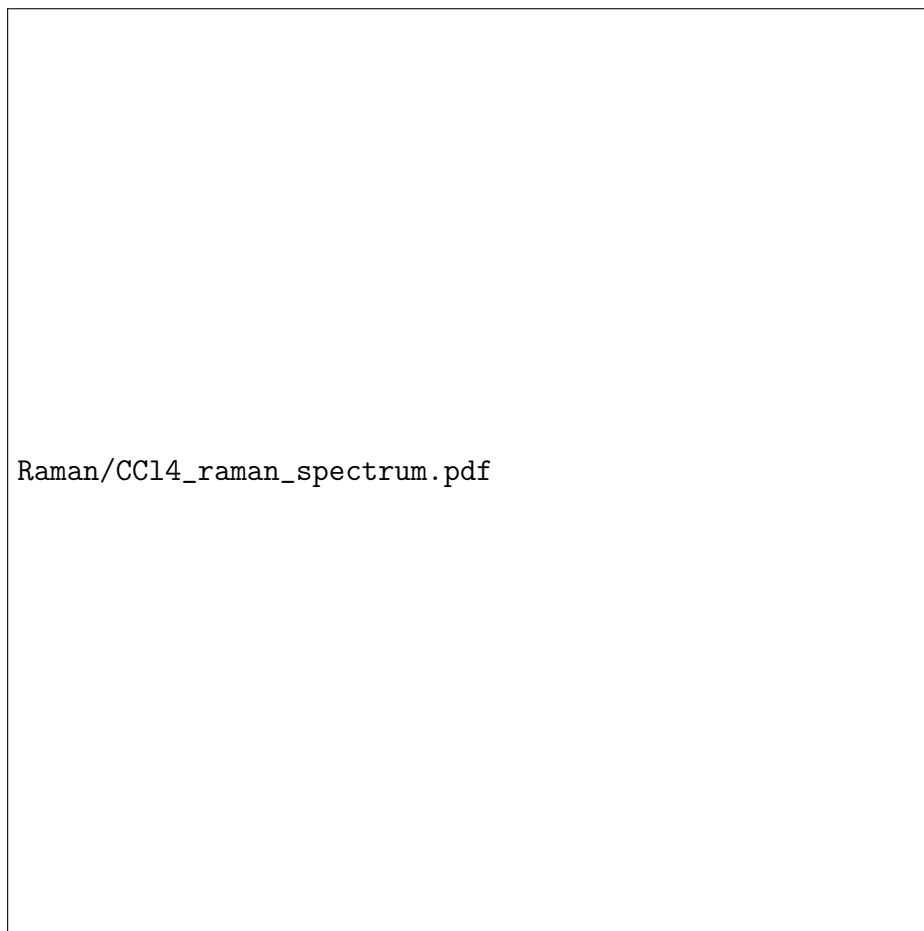


Fig. 8: Measured Raman spectrum of tetrachloromethane.

Tab. 21: Listed are the measured Raman shifts and intensities of the signals of CCl<sub>4</sub>.

Signal	Raman shift $\Delta\tilde{\nu}$ / $\text{cm}^{-1}$	Intensity / a.u.
1	216.25	2831.33
2	308.95	3211.67
3	454.10	4535.33
4	756.86	1849.33

Tab. 22: Listed are the simulated wavenumbers and Raman intensities of the vibrational modes of  $\text{CCl}_4$ .

Mode	Wavenumber $\tilde{\nu}$ / $\text{cm}^{-1}$	Raman intensity / $\text{\AA}^4 \text{ amu}^{-1}$	vibration type
1	212.71	4.18	scissoring
2	212.91	4.17	scissoring
3	310.52	5.39	scissoring
4	310.84	5.40	scissoring
5	311.16	5.40	scissoring
6	451.08	16.40	sym. stretching
7	753.44	1.55	asym. stretching
8	754.26	1.56	asym. stretching
9	754.60	1.54	asym. stretching

## 3.8 Tetrachloroethylene

### 3.8.1 IR

The measured IR spectrum of tetrachloroethylene is shown in ??, plotting the intensity of the absorption against the wavenumber  $\tilde{\nu}$ .



Fig. 9: Measured IR spectrum of tetrachloroethylene.

By visual inspection of the IR spectrum in ??, six absorption signals can be identified, which are listed with their corresponding wavenumbers and intensities in ??.

Tab. 23: Listed are the measured wavenumbers and intensities of the IR signals of  $\text{C}_2\text{Cl}_4$  with the corresponding type of the vibrational mode.

Signal	Wavenumber $\tilde{\nu}$ / $\text{cm}^{-1}$	Intensity / a.u.	Vibration type
1	755.02	0.18	-
2	775.42	0.51	asym. C-Cl stretching
3	799.91	0.18	-
4	903.98	0.88	asym. C-Cl stretching
5	1122.32	0.03	-
6	1354.95	0.01	-

The simulated vibrational modes of tetrachloroethylene are summarized in ?? with the corresponding wavenumber, intensity and vibration type of each mode.

Tab. 24: Listed are the simulated wavenumbers and intensities of the vibrational modes of  $\text{C}_2\text{Cl}_4$ .

Mode	Wavenumber $\tilde{\nu}$ / $\text{cm}^{-1}$	Intensity / $\text{KM}\cdot\text{mol}^{-1}$	Vibration type
1	97.18	0.00	twisting
2	174.89	0.96	scissoring
3	234.77	0.00	scissoring
4	286.90	0.51	wagging
5	310.42	0.03	scissoring
6	342.99	0.00	asym. bending
7	447.02	0.00	sym. stretching
8	514.19	0.00	wagging
9	774.46	82.16	asym. stretching
10	895.52	202.05	asym. stretching
11	978.50	0.00	asym. stretching
12	1624.06	0.00	C = C stretching

As can be seen in ??, the most intense IR-active modes are found at wavenumbers of  $774.46\text{ cm}^{-1}$  and  $895.52\text{ cm}^{-1}$ , which correspond well to the measured signals at  $755.02\text{ cm}^{-1}$  and  $903.98\text{ cm}^{-1}$  in ?. The signals at  $755.02\text{ cm}^{-1}$  and  $799.91\text{ cm}^{-1}$  can be assumed to occur due to isotopic effects, as chlorine has two stable isotopes,  $^{35}\text{Cl}$  and  $^{37}\text{Cl}$ , leading to small shifts in the vibrational frequencies. The two signals above  $1100\text{ cm}^{-1}$  may indicate overtones or combination bands, which are weaker in intensity compared to the fundamental normal modes.

In comparison to the simulated IR spectrum of chloroform with the wavenumbers and vibrational modes in ??, tetrachloroethylene shows additional IR-active modes in the low wavenumber region below  $500\text{ cm}^{-1}$ , which can be attributed to the increased number of atoms in the molecule leading to more vibrational modes.

### 3.8.2 Raman

The measured Raman spectrum of tetrachloroethylene is shown in ??, plotting the Raman intensity against the Raman shift  $\Delta\tilde{\nu}$ .



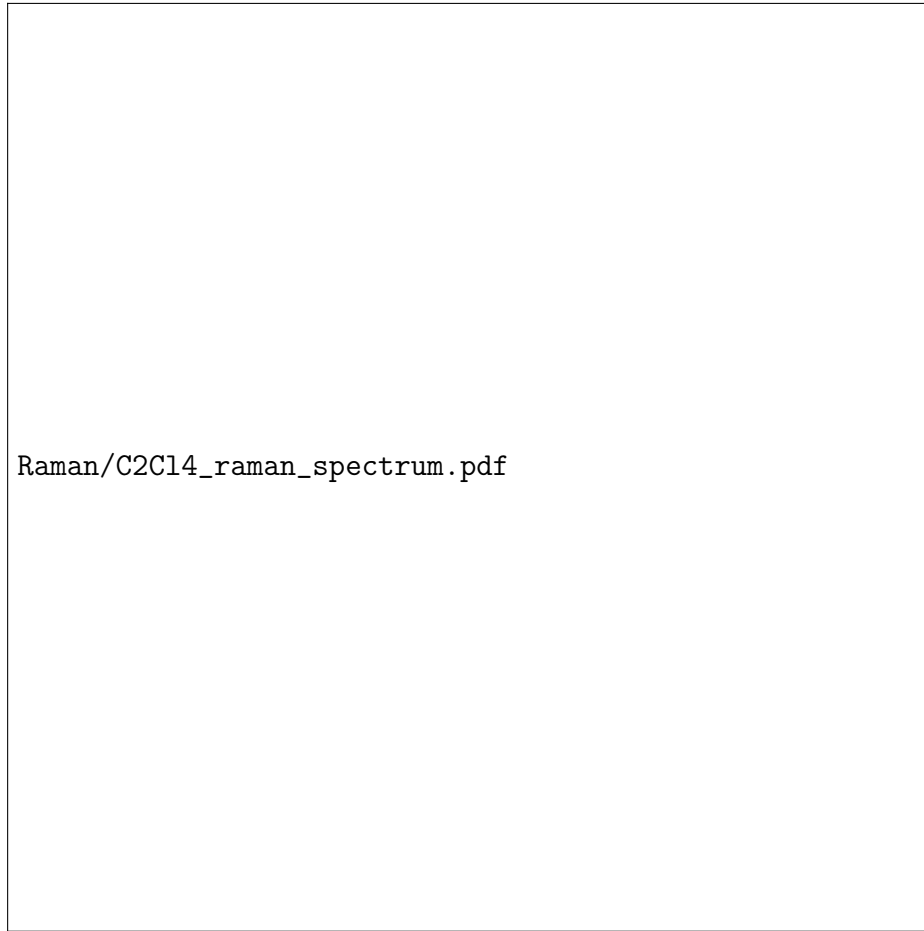


Fig. 10: Measured Raman spectrum of tetrachloroethylene.

By visual inspection of the Raman spectrum in ??, six primary absorption signals can be identified, which are listed with their corresponding Raman shift, Raman intensity and vibration type of each mode.

Tab. 25: Listed are the measured Raman shifts and intensities of the signals of  $\text{C}_2\text{Cl}_4$ .

Signal	Raman shift $\Delta\tilde{\nu}$ / $\text{cm}^{-1}$	Intensity / a.u.	Vibration type
1	231.76	2776.67	scissoring
2	339.67	1879.00	asym. bending
3	442.71	4210.33	sym. stretching
4	1567.61	4313.00	C = C stretching
5	2432.07	2068.33	-

The simulated Raman-active vibrational modes of tetrachloroethylene are summarized in ?? with the corresponding Raman shift, Raman intensity and vibration type of each mode.

Tab. 26: Listed are the simulated wavenumbers and Raman intensities of the vibrational modes of  $\text{C}_2\text{Cl}_4$ .

Mode	Wavenumber $\tilde{\nu}$ / $\text{cm}^{-1}$	Raman intensity / $\text{\AA}^4 \text{amu}^{-1}$	Vibration type
1	97.98	0.00	twisting
2	174.79	0.00	scissoring
3	234.62	5.56	scissoring
4	289.22	0.00	wagging
5	310.02	0.00	scissoring
6	342.83	4.61	asym. bending
7	446.81	15.61	sym. stretching
8	517.38	3.22	wagging
9	774.24	0.00	asym. stretching
10	895.62	0.00	asym. stretching
11	978.54	0.44	asym. stretching
12	1623.90	48.63	C = C stretching

In comparison to the simulated IR-active modes in ??, ?? shows that the most intense Raman-active mode is found at a wavenumber of  $1623.90 \text{ cm}^{-1}$ , which can be assigned to the C = C stretching mode of tetrachloroethylene, which has an intensity of  $0 \text{ KM}\cdot\text{mol}^{-1}$  in the simulated IR spectrum, indicating that it is not IR-active. The cause for this lies in the rule of mutual exclusion, which applies to molecules with a center of symmetry, such as the inversion center of tetrachloroethylene. According to this rule, vibrational modes that are Raman-active are IR-inactive and vice versa, explaining the absence of the  $1623.90 \text{ cm}^{-1}$  mode in the IR spectrum.

By comparing the simulated Raman modes of  $\text{C}_2\text{Cl}_4$  from ?? with the simulated Raman modes of  $\text{CHCl}_3$  in ??, the structural differences between the two molecules can be explained. While both molecules show Raman-active modes in the low wavenumber region below  $500 \text{ cm}^{-1}$ , tetrachloroethylene shows an additional strong Raman-active mode at  $1623.90 \text{ cm}^{-1}$ , which can be attributed to the presence of the C = C double bond in  $\text{C}_2\text{Cl}_4$  that is absent in  $\text{CHCl}_3$ . Additionally, the C-H stretching mode at  $3168.77 \text{ cm}^{-1}$  present in chloroform is not observed in tetrachloroethylene due to the lack of hydrogen atoms in its structure.

## 4 Discussion and Calculations

By plotting the calculated Raman shifts against the vibrational mode number for Methane and all Chloromethanes from ??, ??, ??, ?? and ??, the Raman trends of the investigated molecules can be visualized in ??.

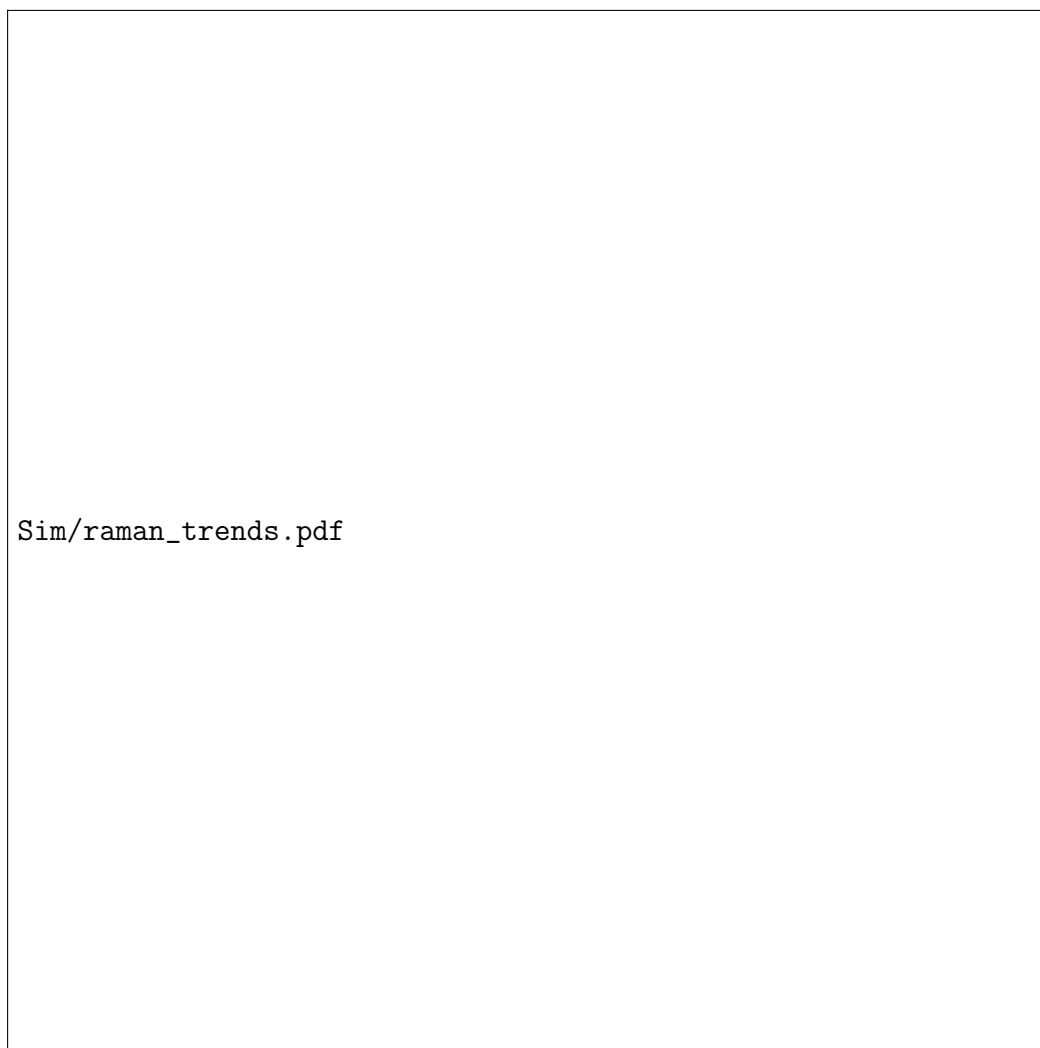


Fig. 11: Raman shifts plotted against the vibrational mode number for  $\text{CH}_4$ ,  $\text{CH}_3\text{Cl}$ ,  $\text{CH}_2\text{Cl}_2$ ,  $\text{CHCl}_3$  and  $\text{CCl}_4$ .

The first trend noticeable in ?? is the decrease of the Raman shifts with increasing number of chlorine atoms in the molecule. This can be explained by the increasing reduced mass  $\mu$  of the molecules according to ?? due to the substitution of hydrogen atoms ( $m = 1$  u) with chlorine atoms ( $m = 35.5$  u).

$$\mu = \frac{m_1 \cdot m_2}{m_1 + m_2} \quad (1)$$

The increasing reduced mass  $\mu$  leads to lower vibrational frequencies  $\nu$  and wavenumbers  $\tilde{\nu}$  according to ?? and ??.

$$\nu = \frac{1}{2\pi} \sqrt{\frac{k}{\mu}} \quad (2)$$

$$\nu = \tilde{\nu} \cdot c \quad (3)$$

Following that argumentation, the number of vibrational modes at around  $3000 \text{ cm}^{-1}$ , which can be assigned to the C-H stretching vibrations, decreases with increasing

number of chlorine atoms in the molecule until no C-H stretching modes are present in tetrachloromethane due to the absence of hydrogen atoms in its structure. In return, new vibrational modes appear in the low wavenumber region below  $1000\text{ cm}^{-1}$ , which can be assigned to the C-Cl stretching vibrations. Another trend observable in ?? is that methane and tetrachloromethane show more vibrational modes with nearly the same Raman shift compared to the other chloromethanes. This can be explained by the high symmetry of both molecules, which belong to the tetrahedral point group  $T_d$ . This trend is especially visible in the triply degenerate asymmetric stretching vibration of methane at  $3150\text{ cm}^{-1}$  and tetrachloromethane at  $754\text{ cm}^{-1}$ .

The Raman signal of the asymmetric C-H stretching vibration of dibromomethane at  $3062.11\text{ cm}^{-1}$  in ?? shows a higher Raman shift and Raman intensity than the corresponding signal of dichloromethane at  $3051.13\text{ cm}^{-1}$  in ?. The higher Raman intensity can be explained by the higher polarizability of the electrons in bromine atoms compared to chlorine atoms, leading to a larger change in polarizability during the vibration and thus a stronger Raman signal.

For the comparison of the C-Cl and C-Br force constants, the reduced masses  $\mu$  for both bonds are calculated using ??

$$\mu_{\text{C-Cl}} = \frac{12 \frac{\text{g}}{\text{mol}} \cdot 35.5 \frac{\text{g}}{\text{mol}}}{12 \frac{\text{g}}{\text{mol}} + 35.5 \frac{\text{g}}{\text{mol}}} = 8.97 \frac{\text{g}}{\text{mol}}$$

$$\mu_{\text{C-Br}} = \frac{12 \frac{\text{g}}{\text{mol}} \cdot 79.9 \frac{\text{g}}{\text{mol}}}{12 \frac{\text{g}}{\text{mol}} + 79.9 \frac{\text{g}}{\text{mol}}} = 10.43 \frac{\text{g}}{\text{mol}}$$

By rearranging ?? and inserting  $\nu$  from ?? the force constant  $k$  can be calculated with ??

$$k = (2\pi \cdot \nu)^2 \cdot \mu = (2\pi \cdot \tilde{\nu} \cdot c)^2 \cdot \mu \quad (4)$$

By inserting the calculated

## 5 Conclusion

## 6 References

- [1] H. Dilger, *2025-pc2-script-en*, **2025**.