The Raman spectrum of isolated water clusters

Katharina E. Otto, Zhifeng Xue, Philipp Zielke and Martin A. Suhm*

Cold water oligomers (H$_2$O)$_n$ and (D$_2$O)$_n$ with $n = 2$–5 are assigned in spontaneous Raman scattering spectra of seeded rare gas expansions for the first time. Comparison with infrared spectra provides direct experimental insights into the hydrogen bond-mediated excitonic OH oscillator coupling, which is responsible for ultrafast energy transfer between water molecules, usually suppressed by isotopic dilution in femtosecond experiments for the condensed phase. The experimental coupling constants are compared to those in state-of-the-art full-dimensional water potential energy hypersurfaces, leaving room for improvement in the description of the coupled dynamics in water. Evidence for intensified Fermi resonance between OH stretching and OH bending motion beyond water trimers is collected.

1 Introduction

The vibrational dynamics of water is of fundamental interest. It is mediated by a network of intermolecular hydrogen bonds, which can be introduced step by step in the popular cluster approach. While matrix isolation and chromophore labeling have proven useful in this context, the study of unperturbed, isolated water clusters is particularly attractive due to the close contact with theory and the large amplitude motion in these systems. Direct infrared and microwave studies have become available in recent years and have provided detailed information on nuclear quantum effects and electronic cooperativity, in particular when combined with theoretical predictions. Although the Raman selection rules provide essential complementary information on concerted motions, only a pioneering coherent anti-Stokes Raman spectroscopy (CARS) investigation of isolated water clusters has so far been published and discussed controversially. The nonlinearity of the CARS experiment rendered a firm assignment of cluster sizes difficult. Therefore, the characteristic coupling between neighboring OH oscillators in water assemblies, which controls energy flow after local excitation, has remained largely in the dark.

This is where the present contribution sets in. By generating isolated, internally cold, small water clusters in slit jet expansions of an atomic carrier gas into vacuum and probing them by an intense visible laser, sufficient numbers of spontaneously Raman-scattered photons are generated to detect OH stretching modes which show negligible infrared intensity and have thus remained unassigned in the gas phase to date. The strong hydrogen bond cooperativity ensures a sufficient spread of the signals on the wavenumber axis for a reliable cluster size separation and size assignment based on stagnation pressure, nozzle temperature, polarization dependence and water concentration dependence up to at least five water units. Further support for the vibrational and size assignment comes from equivalent experiments with D$_2$O. This compensates for the lack of rigorous size selection. The combination with corresponding IR data then leads to an effective approach to the oscillator coupling within a simple framework of Hückel-like coupling matrices, as exemplified in the case of cyclic methanol clusters. The energy splitting of the degenerate monomer oscillators into symmetric and asymmetric linear combinations in a cyclic cluster is caused by coupling through space or through the connecting hydrogen bonds.

These coupled modes are observable as a mode pattern in the frequency domain, but their importance is better visualized in the time domain. Excitation of a local OH stretching mode by a suitable ultrashort laser pulse would lead to a rapid delocalization of the excitation energy among the coupled oscillators as a function of time. In a finite cluster and in the absence of other redistribution mechanisms, this is a periodic process which ultimately leads to a refocussing of the energy in the original oscillator. In liquid or solid water, the energy is dissipated irreversibly. Although the detailed quantum dynamics can be complex, there is a reciprocal relationship between the magnitude of the excitonic splitting and the lifetime of the localized state. The larger the spectral splitting, the faster the energy dissipation. Therefore, the size of the coupling constant between OH stretching modes in a water cluster is of

---

Institut für Physikalische Chemie, Georg-August-Universität Göttingen, Tammannstraße 6, 37077 Göttingen, Germany. E-mail: msuhm@gwdg.de; Fax: +49 551 3933117; Tel: +49 551 3933112

† Electronic supplementary information (ESI) available: Rotational temperature analysis based on Stokes and anti-Stokes intensities; detailed descriptions of spectra and experimental conditions; depolarization analysis; matrix isolation trends; and more extensive quantum chemical compilations. See DOI: 10.1039/c3cp54272f
The symmetric stretching fundamental will be presented and assigned. The discussion of excitonic patterns in the cyclic clusters will start with the most clearcut tetramer case and extend to the trimer and pentamer, followed by preliminary assignments of non-cyclic hexamer bands.

2 Experimental setup

Gas mixtures of water with He, Ne/He or Ar/He were expanded via a $4 \times 0.15$ mm$^2$ or $8 \times 0.05$ mm$^2$ heatable slit nozzle into an aluminium chamber, pumped using two Roots pumps ($500$ m$^3$ h$^{-1}$ and $250$ m$^3$ h$^{-1}$) and one rotary vane pump ($100$ m$^3$ h$^{-1}$). The beam of a frequency doubled cw NdVO$_4$ Laser (Coherent Verdi V18, $18$ W, $\lambda = 532$ nm) was focused onto the expansion at $2$ mm distance from the nozzle exit. The scattered light was collected perpendicularly to the expansion and to the incident laser beam and collimated using a fast camera lens ($50$ mm Nikon, $f/1.2$). It was then focused onto the entrance slit of the monochromator (McPherson Model 2051, $f/8.6, f = 1000$ mm, grating $1200$ grooves per mm or McPherson Model 205f, $f/3.2, f = 500$ mm, grating $600$ gr per mm) using an achromatic planoconvex lens (Edmund Optics, $\Theta = 50$ mm, $f/7$ for McPherson Model 2051 and Edmund Optics, $\Theta = 50$ mm, $f/4$ for McPherson Model 205f). Suppression of the Rayleigh scattered light was achieved using a Raman edge filter (L.O.T., $\Theta = 25$ mm, OD $6.0, T > 90\%$, $535.4-1200$ nm). A back-illuminated CCD camera (PI Acton, Spec-10: $400$ B/LN, $1340 \times 400$ pixels, cooled by liquid $N_2$) served for detection in a vertical binning mode. Count rates refer to the full $400$-pixel columns. The wavelength calibration of the spectra was carried out using the lines of a Ne I emission light source and H$_2$O monomer Raman transitions. Cosmic ray signals were removed by the comparison of block-averaged spectra. Polarization experiments were performed by rotating the laser beam via a $\lambda/2$-plate.

The Stokes scattering was probed from $80$ to $8000$ cm$^{-1}$, but here we concentrate on the by far strongest Raman cluster signals between $3000$ and $4000$ cm$^{-1}$, in the region of the OH stretching fundamentals and the OH bending overtones.

3 Results and discussion

3.1 Spectral survey

In supersonic jet expansions, different molecular degrees of freedom may have different effective temperatures or even non-thermal distributions. We obtained monomer rotational temperatures of $30-50$ K based on the relative intensities of Stokes and anti-Stokes transitions (see ESI† for details). These are in qualitative agreement with recent results for cluster-free expansions of water in helium, considering the large differences in expansion conditions. Vibrational temperatures are probably higher and lead to relatively broad band contours with occasional hot band features, marked with * in the following spectra. The temperatures can be lowered by variation of the stagnation conditions and carrier gas.

Fig. 2 and 3 contain a collection of Raman supersonic jet spectra for H$_2$O and D$_2$O expansions in different carrier gases and under varying conditions (described in detail in the ESI†). Their spectral windows have been matched by D$_2$O wavenumber...
axis stretching ($\times 1.508$) and monomer symmetric stretch band center alignment. The correspondence between the isotopologues is indeed very close. Studies of the carrier gas dependence and of the depolarization ratio are provided in the ESL.† Table 1 provides peak positions and explains the labels of the Raman spectral features. Also shown in the upper right traces and in Table 1 are corresponding FTIR supersonic jet spectra, which agree with earlier laser spectroscopy observations.18,39

The high degree of complementarity for trimers (3b), tetramers (4b) and pentamers (5b) is a consequence of their ring topology.
The Raman spectra are dominated by the sharp symmetric OH stretching transitions of the monomer, some of which are labeled (1). Between the symmetric and antisymmetric water monomer bands, a structured scattering signal from dangling (free) OH groups is found. Contributions from dimers (2f), trimers (>2f), larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f)

The symmetry labels A, E, B derive from the S_4 point group. The degenerate pair of E transitions, which is predominantly IR-active, is thus separated by W_3 from the center of the coupling pattern, whereas the predominantly Raman-active A transition is below the center, by 2W_1 + W_2. This A level was recently predicted to have an intracluster energy redistribution rate of 0.4 ps.29 The observed width of the Raman transition of 10 cm^{-1} is qualitatively still compatible with this rate in the limit of a dense manifold of coupling states, but actually more narrow than the corresponding IR mode. The B-transition is expected to have a weak intensity in both types of spectra. The splitting between the IR-active and dominant Raman active bands (E/A) is thus 2W_1 + W_2. Between the weaker Raman-active and the IR-active bands (B/E) it is 2W_1 - 2W_2, and between the two Raman active bands (B/A) 4W_1. As the assignment of the second Raman active band is less certain, we define a composite coupling constant W_4 = W_1 + W_2 which only depends on the strong Raman and IR transitions (corresponding to one half of the E/A separation) and allows for a safer comparison between theory and experiment. The experimental error of W_4 may be conservatively estimated to be around ±2 cm^{-1} as one half of the sum of the Raman calibration error of ±1 cm^{-1} and possible differences between band centers and band maxima in the IR and Raman spectra of up to 3 cm^{-1}, which should however largely cancel in the spectral difference.

Depending on the spectral assignments, there are three different ways to analyze the coupling multiplet in the water tetramer. If one neglects couplings beyond the nearest neighbors (W_2), the direct coupling constant based on the most active A-symmetric (Raman) and E-symmetric (IR) vibrations is W_4 ≈ W_1 = 34 cm^{-1}, which is to be compared to 12–13 cm^{-1} from the most recent and otherwise fairly accurate analytical potential hypersurface.42 One could argue that the discrepancy stems from the neglect of next-nearest neighbor coupling. Indeed, inclusion of the weakly Raman-active B-transition at 3438 cm^{-1} reduces the experimental nearest-neighbor coupling

The same zeroth order wavenumber and couples directly to its hydrogen bond acceptor partner and either along two hydrogen bonds or across the diagonal to its next-nearest neighbor. The direct coupling is described by W_4 and the weaker diagonal coupling by W_2. A Hückel-like analysis39 of the combined action of all couplings leads to the determinant equation

\[
\begin{vmatrix}
 x & W_1 & W_2 & W_1 \\
 W_1 & x & W_1 & W_2 \\
 W_2 & W_1 & x & W_1 \\
 W_1 & W_2 & W_1 & x \\
\end{vmatrix} = 0
\]

the solutions of which are

\[
x_1 = -2W_1 - W_2 \quad (A)
\]
\[
x_{2,3} = W_2 \quad (E)
\]
\[
x_4 = 2W_1 - W_2 \quad (B)
\]

The Raman spectra are dominated by the sharp symmetric OH stretching transitions of the monomer, some of which are labeled (1). Between the symmetric and antisymmetric water monomer bands, a structured scattering signal from dangling (free) OH groups is found. Contributions from dimers (2f), trimers (>2f), larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significantly larger (>3f) and significantly larger (>3f, >2f), larger (>3f) and significan
to \( W_1 = 26 \text{ cm}^{-1} \) by compensating with a distant coupling term across the ring of \( W_2 = 8 \text{ cm}^{-1} \). This does not improve the agreement with theory, because such a second-nearest neighbor interaction is essentially absent from the most recent analytical potential energy hypersurfaces. In contrast, even simple harmonic \( \text{ab initio} \) calculations yield largely correct orders of magnitude, also in line with experiments for methanol tetramers.\(^{19}\) If one does not want to rely on the less certain orders of magnitude, also in line with experiments for methanol tetramers, the coupling constants shrink by 30–40%, as in methanol.\(^{19}\) The tabulated sum \( W_4 = W_1 + W_2 \) is particularly robust from the experimental point of view.

Table 2 Different theoretical results for the nearest neighbor (\( W_1 \)) and distant (\( W_2 \)) coupling parameters of the hydrogen-bonded OH stretching manifold of the water tetramer compared to the present experimental results for (\( H_2 O \))\(_4\) as well as the more strongly bound "methylated" water tetramers.\(^{19}\) The tabulated sum \( W_4 = W_1 + W_2 \) is particularly robust from the experimental point of view.

<table>
<thead>
<tr>
<th>Method</th>
<th>Variant</th>
<th>Electronic structure</th>
<th>( W_1/\text{cm}^{-1} )</th>
<th>( W_2/\text{cm}^{-1} )</th>
<th>( (W_1 + W_2)/\text{cm}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harmonic(^{44})</td>
<td>BSSE-corrected</td>
<td>B3LYP/6-311+G(d,pVTZ)</td>
<td>32</td>
<td>13</td>
<td>45</td>
</tr>
<tr>
<td>Vibrational CI(^{44})</td>
<td>BSSE-corrected</td>
<td>MP2/6-311+G(2d,2p)</td>
<td>25</td>
<td>10</td>
<td>35</td>
</tr>
<tr>
<td>Vibrational CI(^{44})</td>
<td>With BSSE</td>
<td>MP2/6-311+G(2d,2p)</td>
<td>21</td>
<td>11</td>
<td>32</td>
</tr>
<tr>
<td>Harmonic(^{42})</td>
<td></td>
<td>CCSD(T)/aug-cc-pVDZ</td>
<td>28</td>
<td>12</td>
<td>40</td>
</tr>
<tr>
<td>Harmonic(^{42})</td>
<td></td>
<td>LCCSD(T)/aug-cc-pVDZ</td>
<td>20</td>
<td>7</td>
<td>26</td>
</tr>
<tr>
<td>Harmonic(^{42})</td>
<td></td>
<td>LCCSD(T)/aug-cc-pVTZ</td>
<td>23</td>
<td>9</td>
<td>32</td>
</tr>
<tr>
<td>Harmonic(^{42})</td>
<td>No 4-body terms</td>
<td>PES(1,2,3)</td>
<td>13</td>
<td>5</td>
<td>18</td>
</tr>
<tr>
<td>Harmonic(^{26})</td>
<td>Full-dimensional</td>
<td>WHBB-surface</td>
<td>13</td>
<td>1</td>
<td>13</td>
</tr>
<tr>
<td>Harmonic(^{42})</td>
<td>LMon-( \beta )_{full}</td>
<td>WHBB-surface</td>
<td>13</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td>Anharmonic(^{43})</td>
<td>LMon-( \beta )_{full}</td>
<td>WHBB-surface</td>
<td>12</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>Anharmonic(^{43})</td>
<td>MP2 VPT2 est.</td>
<td>CCSD(T)/aug-cc-pVDZ</td>
<td>21</td>
<td>7</td>
<td>28</td>
</tr>
<tr>
<td>Experiment ( D_2 O )</td>
<td>IR + Raman</td>
<td>Non-Born–Oppenheimer</td>
<td>17</td>
<td>5</td>
<td>22</td>
</tr>
<tr>
<td>Experiment ( CH_3 OH )</td>
<td>IR + Raman</td>
<td>Non-Born–Oppenheimer</td>
<td>29</td>
<td>11</td>
<td>40</td>
</tr>
<tr>
<td>Experiment ( CH_3 OD )</td>
<td>IR + Raman</td>
<td>Non-Born–Oppenheimer</td>
<td>23</td>
<td>8</td>
<td>31</td>
</tr>
</tbody>
</table>

In view of the involved simplifications, the agreement between experiment and harmonic \( \text{ab initio} \) calculations is remarkably good for the \( \{H_2 O\}_4 \) coupling constants. While the B3LYP calculations\(^43\) somewhat overestimate the coupling, available BSSE-corrected MP2 and higher level electron correlation treatments\(^{42,46}\) agree with experiment within the uncertainties of the latter and vibrational CI treatment does not change the values substantially.\(^6\) This contrasts with the performance of analytical potential energy surfaces derived from these highly correlated calculations,\(^{26,42}\) independent of whether the latter include higher than three-body terms and whether they are evaluated harmonically or within anharmonic approximations.\(^{26}\)

Clearly, the OH mode coupling in the most accurate analytical water potentials is underestimated, possibly at the level of specific coupling terms in the analytical many-body expansion.

We emphasize that the experimental data are quite robust, at least concerning \( W_4 \), which only relies on the dominant transitions of each spectroscopic technique. It appears that coupling among the OH oscillators, and thus resonant energy flow along the OH stretching modes, is underestimated by at least a factor of two in the most accurate analytical fits. Since the multi-dimensional fits are truly challenging and the investigated quantity is relatively subtle, this is not an unexpected performance, but the present experiments for the first time provide solid evidence and incentive to improve the flexibility of this particular coordinate coupling. However, in order to exclude a coincidental mismatch, it is necessary to turn to the more difficult trimer case.

### 3.3 Water trimer

For the cyclic trimer (ref. 4 and references cited therein) one has to distinguish between a \( C_3 \) symmetric aggregate (simple Hückel model) where coupling constants between the three oscillators are equal and an asymmetric coupling case where the H-bonds differ in strength.\(^{19}\) For the first case the solutions

\[
\begin{align*}
&x & W & W \\
&W & x & W \\
&W & W & x
\end{align*}
\]

are:

\( x_1 = -2W_4 \) \hspace{1cm} \( x_{2,3} = W \)

Therefore the coupling constant \( W \) corresponds to the splitting between the Raman and IR active levels divided by 3.

In the latter case one obtains two different coupling constants \( W_1, W_2 \) and the determinant equation

\[
\begin{vmatrix}
W_1 & W_2 \\
W_1 & W_2
\end{vmatrix} = 0
\]

\hspace{1cm} (5)
Its solutions are:

\[
x_1 = -\frac{\sqrt{8W_1^2 + W_2^2} - W_2}{2}
\]

\[
x_2 = W_2
\]

\[
x_3 = \frac{\sqrt{8W_1^2 + W_2^2} - W_2}{2}
\]

The splitting between the highest and lowest level is therefore \(\sqrt{8W_1^2 + W_2^2}\) and the inner level is separated from the center of the multiplet by \(W_2\).

The experimental infrared OH stretching spectrum of the water trimer has been studied in different environments. It consists of a main band and a satellite, which is often, but not always located at higher frequency. Upon deuteration, this satellite peak disappears, hinting at a possible tunneling origin. Fig. S8 in the ESI discusses the phenomenological situation in comparison to the tetramer. Comparison between experiment and theory depends on whether one interprets the weak satellite in the IR as one of the near-degenerate OH stretching modes or not. The ESI peak disappears, hinting at a possible tunneling origin. Fig. S8 in the ESI discusses the phenomenological situation in comparison to the tetramer. Comparison between experiment and theory depends on whether one interprets the weak satellite in the IR as one of the near-degenerate OH stretching modes or not. The maximum spread of the OH stretching modes is either 57 cm\(^{-1}\) or else \(\approx 42\) cm\(^{-1}\). A more likely value is in between, if one interprets the center of gravity of the two IR bands as the proper reference. On the theoretical side, two fit variants of the three body potential yield a spread of the bound OH stretching modes of 50 vs. 29 cm\(^{-1}\) for the water trimer. Matrix isolation IR studies\(^4\) find a large sensitivity of the trimer stretching spectra and their intensities to the environment. The Ne matrix isolation value for the exciton splitting\(^5\) of 57 cm\(^{-1}\) is consistent with our gas phase findings, in particular considering actual matrix-shifts of 15–19 cm\(^{-1}\) in this case.

The non-equivalence of the three hydrogen bonds in the trimer can be included in the analysis and adds further to the uncertainty. In Table 3, we list the experimentally derived trimer coupling constants according to the symmetric (\(W = W_3\)) and the asymmetric models (\(W_1, W_2\)). For the regular hydrogen isotope, we distinguish between the interpretation of the main IR peak as the quasidegenerate E band (case 3\(a\)) and the interpretation of both observed peaks as the components of the E band despite their different intensities and large splitting (less likely case 3\(b\)). Despite the assignment uncertainty, one can see that the \(W\) coupling constants show the expected trend with deuteration (decrease) and methyl group substitution (increase), as in the case of the tetramer. When comparing to theory, we always interpret the (now equally intense and more closely spaced) IR doublet in the sense of model 3\(b\) when extracting a symmetric coupling constant \(W\). The performance of harmonically predicted coupling constants is again remarkable, quite independent of the level of computation, as Table 3 shows. The coupling pattern appears to be rather robust, as expected for a transition dipole or hydrogen bond mediated interaction. This is also the case for one of the analytical WHBB (Wang/Huang/Braams/Bowman) fits to the high level \(\text{ab initio}\) data, namely the variant 3b6 for the three body contribution. On the other hand, the 3b5 fit only recovers about half of the coupling. As this parametrization appears to have been used for the tetramer predictions,\(^26,51\) this may contribute to the discrepancies discussed in the previous section.

### 3.4 Tentative pentamer analysis

For the cyclic water pentamer, the absence of symmetry\(^52\) complicates the coupling analysis and several assumptions are necessary to analyze the experimental coupling pattern. We assume an averaged effective \(C_{5v}\) symmetry, instead of the puckered non-planar ring. Based on simple connectivity considerations, the nearest and next-nearest neighbor excitonic splittings are determined from the following equation:

\[
\begin{vmatrix}
    x & W_1 & W_2 & W_3 \\
    W_1 & x & W_2 & W_3 \\
    W_2 & W_1 & x & W_3 \\
    W_3 & W_2 & W_1 & x
\end{vmatrix} = 0
\]

### Table 3

<table>
<thead>
<tr>
<th>Method</th>
<th>Variant</th>
<th>Electronic structure</th>
<th>(W/cm^{-1})</th>
<th>(W_3/cm^{-1})</th>
<th>(W_5/cm^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harmonic(^44)</td>
<td>BSSE-corrected</td>
<td>MP2/6-311+G(2d,2p)</td>
<td>17</td>
<td>19</td>
<td>13</td>
</tr>
<tr>
<td>Vibrational CI(^44)</td>
<td>BSSE-corrected</td>
<td>MP2/6-311+G(2d,2p)</td>
<td>19</td>
<td>21</td>
<td>16</td>
</tr>
<tr>
<td>Vibrational CI(^44)</td>
<td>With BSSE</td>
<td>MP2/6-311+G(2d,2p)</td>
<td>19</td>
<td>21</td>
<td>16</td>
</tr>
<tr>
<td>Harmonic(^42)</td>
<td>3b5 fit</td>
<td>WHBB-surface</td>
<td>8</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Harmonic(^40)</td>
<td>3b6 fit</td>
<td>WHBB-surface</td>
<td>15</td>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td>Anharmonic(^45)</td>
<td>MP2 VPT2 est.</td>
<td>CCSD(T)/aug-cc-pVDTZ</td>
<td>18</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Experiment H(_2)O (3(a))</td>
<td>IR + Raman</td>
<td>Non-Born–Oppenheimer</td>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Experiment H(_2)O (3(a))</td>
<td>IR + Raman</td>
<td>Non-Born–Oppenheimer</td>
<td>17</td>
<td>20</td>
<td>9</td>
</tr>
<tr>
<td>Experiment D(_2)O</td>
<td>IR + Raman</td>
<td>Non-Born–Oppenheimer</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Experiment CH(_3)OH(^19)</td>
<td>IR + Raman</td>
<td>Non-Born–Oppenheimer</td>
<td>20</td>
<td>21</td>
<td>17</td>
</tr>
<tr>
<td>Experiment CH(_2)OD(^19)</td>
<td>IR + Raman</td>
<td>Non-Born–Oppenheimer</td>
<td>13</td>
<td>14</td>
<td>11</td>
</tr>
</tbody>
</table>

This journal is © the Owner Societies 2014
The splitting between NMR IR bands is thus $W = 2g + \omega_0$, whereas the splitting between two Raman active bands is $W = 2g + \omega_0$. In a puckered ring, the degenerate states will be further split by a small amount. Because the highest frequency transition is not predicted to be strong in either IR or Raman spectra, it is desirable to have a linear combination of coupling constants $W$ which does not depend on its assignment. This is given by $W^2 = W_1^2 + \frac{\sqrt{5} + 1}{\sqrt{5} - 1} W_2$, which we therefore use as a robust measure for pentameric exciton coupling. As in the case of $W_4$, $W_5$ corresponds to the nearest neighbor coupling $W_1$ if more distant couplings are neglected. The experimental error in $W_5$ is less than $\pm 0.3 \text{ cm}^{-1}$, if we assume a conservative error in the IR/Raman-splitting of 4 cm$^{-1}$.

Turning now to the experimental spectra, the dominant IR/Raman water pentamer signals (Fig. 2 and 3) are closer together than the tetramer peaks, despite a reduced ring strain and enhanced cooperativity in the cyclic hydrogen bond pattern. Only the deuterated water spectra offer an assignment of all three bands, if the band at 2500 cm$^{-1}$ is the corresponding tetramer values of 17 and 5 cm$^{-1}$. One then obtains $W_4 = 14 \text{ cm}^{-1}$ and $W_5 = 4 \text{ cm}^{-1}$, which may be compared with the corresponding tetramer values of 17 and 5 cm$^{-1}$, respectively. The coupling parameter $W_5$, which only depends on the strong IR and Raman features, is also systematically smaller than for the theoretical harmonic predictions, even at levels that were shown to be quite successful for tetramers and trimers (see Table 4). We think that the explanation is of an anharmonic nature. For this, the region around 3200 cm$^{-1}$ (2400 cm$^{-1}$ for D$_2$O) must be addressed. Blue-shifted to the Raman transitions of the first monomer OH bending overtone (1o), there is a polarized signal (>3o) near 3214 cm$^{-1}$ which has an intensity evolution typical for a mix of ring tetramers and pentamers. This is illustrated in Fig. 4. Its IR counterparts are weak and somewhat shifted (see Fig. 2 and 3), suggesting a dominant ring cluster contribution. In Ne matrices, a blue-shifted trimer bending overtone has been reported at 3190 cm$^{-1}$. Normally, one would expect much less Raman intensity for such a cluster transition, due to the dominance of monomers in the expansions. Furthermore, a coincidence of tetramer and pentamer signals is unlikely in an unperturbed picture. The progressively smaller energy gap between the OH stretching fundamentals (4b, 5b) and the OH bending overtone (>3o) explains both anomalies by an increasing extent of Fermi resonance between the two states (see Fig. 1), relative to the trimer. The pentamer may have a somewhat higher bending overtone visibility and experience a reduced overtone frequency due to this anharmonic interaction. That is particularly true for the highest frequency concerted bending modes, which are expected to couple most to the Raman active concerted OH stretching modes (Fig. 1).

As a consequence, the latter are shifted to higher frequency, more so in the pentamer than in the tetramer. Indeed, simple model calculations show that the energy coincidence is close in the pentamer. This is illustrated in Table 5, which uses published density functional data to predict the energy coincidence between the experimental stretching fundamental $4b$ and the anharmonic bend overtones. The latter are estimated from the experimental monomer bend overtone and the calculated complexation shift in the fundamental region. Fermi resonance is more likely if the depolarization ratio is low (like in the

### Table 4

<table>
<thead>
<tr>
<th>Method</th>
<th>Variant</th>
<th>Electronic structure</th>
<th>$W_4$/cm$^{-1}$</th>
<th>$W_5$/cm$^{-1}$</th>
<th>$W_2$/cm$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harmonic$^{52}$</td>
<td></td>
<td>MP2/aug-cc-pVDZ</td>
<td>35</td>
<td>9</td>
<td>58</td>
</tr>
<tr>
<td>Harmonic$^{43}$</td>
<td>Scaled</td>
<td>B3LYP/d-aug-cc-pVDZ</td>
<td>34</td>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>Harmonic$^{44}$</td>
<td>BSSE-corrected</td>
<td>MP2/6-311+G(2d,2p)</td>
<td>26</td>
<td>7</td>
<td>45</td>
</tr>
<tr>
<td>Vibrational Cl$^{44}$</td>
<td>BSSE-corrected</td>
<td>MP2/6-311+G(2d,2p)</td>
<td>26</td>
<td>6</td>
<td>42</td>
</tr>
<tr>
<td>Vibrational Cl$^{44}$</td>
<td>With BSSE</td>
<td>MP2/6-311+G(2d,2p)</td>
<td>43</td>
<td>34</td>
<td>133</td>
</tr>
<tr>
<td>Harmonic$^{26}$</td>
<td>Full-dimensional</td>
<td>WHBB</td>
<td>14</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td>Harmonic$^{26}$</td>
<td>LMon-\beta\text{dimer}</td>
<td>WHBB</td>
<td>14</td>
<td>0</td>
<td>14</td>
</tr>
<tr>
<td>Harmonic$^{26}$</td>
<td>LMon-\beta\text{dimer}</td>
<td>WHBB</td>
<td>15</td>
<td>0</td>
<td>14</td>
</tr>
<tr>
<td>Harmonic$^{47}$</td>
<td>CCSD[T]/aug-cc-pVDZ</td>
<td>CCSD[T]/aug-cc-pVDZ</td>
<td>30</td>
<td>9</td>
<td>53</td>
</tr>
<tr>
<td>Anharmonic$^{45}$</td>
<td>MP2 VPT2 est.</td>
<td>Non-Born–Oppenheimer</td>
<td>—</td>
<td>—</td>
<td>33</td>
</tr>
<tr>
<td>Experiment H$_2$O</td>
<td>IR + Raman</td>
<td>Non-Born–Oppenheimer</td>
<td>24</td>
<td>8</td>
<td>44</td>
</tr>
<tr>
<td>Experiment D$_2$O</td>
<td>IR + Raman</td>
<td>Non-Born–Oppenheimer</td>
<td>14</td>
<td>4</td>
<td>25</td>
</tr>
</tbody>
</table>
resonance coupling parameter (smaller in the D$_2$O case), but the redistribution lifetime\textsuperscript{29} for the tetramer after Raman-active OH overtone is also responsible for the short predicted energy mental study for cyclic water clusters provide valuable constraints. Effects of intra-monomer coupling should be smaller in the case of cyclic water clusters, because the strong hydrogen bonds decouple the free and the bound OH stretching modes quite effectively.

The excitonic coupling constants obtained in this experimental study for cyclic water clusters provide valuable constraints on harmonic,\textsuperscript{20} anharmonic\textsuperscript{26,44} and empirical\textsuperscript{46} models for the

### 4 Conclusions

The first spontaneous Raman scattering spectra of small water clusters offer quantitative insights into the coherent energy hopping of localized OH stretching excitations from one molecule to another, when compared to existing IR spectra. This is related to the non-coincidence effect,\textsuperscript{52} which can be spectrally resolved in the case of cold clusters.\textsuperscript{23} Table 6 summarizes the robust OH and OD oscillator coupling constants for the water trimer (W3), the tetramer (W4) and the pentamer (W5). The deuteration and methylation\textsuperscript{19} effects are systematic and expected. The ring size dependence is unusually weak beyond the tetramer, which we explain by the growing importance of stretch-bend Fermi resonance for the symmetric modes. Effects of intra-monomer coupling should be smaller in the case of cyclic water clusters, because the strong hydrogen bonds decouple the free and the bound OH stretching modes quite effectively.

The excitonic coupling constants obtained in this experimental study for cyclic water clusters provide valuable constraints on harmonic,\textsuperscript{20} anharmonic\textsuperscript{26,44} and empirical\textsuperscript{46} models for the

### Table 5

<table>
<thead>
<tr>
<th>Cluster size</th>
<th>$\nu_{\text{bend}}$ (cm$^{-1}$)</th>
<th>$\rho$</th>
<th>$\gamma$ (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1622</td>
<td>0.68</td>
<td>504</td>
</tr>
<tr>
<td>3</td>
<td>1658</td>
<td>0.39</td>
<td>266</td>
</tr>
<tr>
<td></td>
<td>1634</td>
<td>0.64</td>
<td>314</td>
</tr>
<tr>
<td></td>
<td>1631</td>
<td>0.75</td>
<td>320</td>
</tr>
<tr>
<td>4</td>
<td>1681</td>
<td>0.25</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>1651</td>
<td>0.75</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td>1636</td>
<td>0.75</td>
<td>153</td>
</tr>
<tr>
<td>5</td>
<td>1689</td>
<td>0.17</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>1681</td>
<td>0.05</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>1660</td>
<td>0.74</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>1652</td>
<td>0.62</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>1640</td>
<td>0.73</td>
<td>121</td>
</tr>
</tbody>
</table>

### Table 6

<table>
<thead>
<tr>
<th>M</th>
<th>W3/cm$^{-1}$</th>
<th>W4/cm$^{-1}$</th>
<th>W5/cm$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$O</td>
<td>14–17</td>
<td>34</td>
<td>33</td>
</tr>
<tr>
<td>D$_2$O</td>
<td>11</td>
<td>22</td>
<td>25</td>
</tr>
<tr>
<td>CH$_3$OH\textsuperscript{19}</td>
<td>20</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>
vibrational dynamics in hydrogen-bonded systems and water in particular. In a somewhat model-dependent way, they can be interpreted within a time-dependent framework. Already for the trimer, the splittings are consistent with a drop of any local excitation to $1/e$ within about 0.3 ps.\textsuperscript{19,27} For tetramers and pentamers, the coherent transfer to neighboring modes will be even faster. In an extended network such as liquid water, this decay becomes irreversible and it qualitatively explains the even faster. In an extended network such as liquid water, this hydrogen bond-induced excitonic splitting is a subtle, yet crucial ingredient for multidimensional cluster potential energy surfaces, in particular for the smallest clusters of the most important molecule on earth.

**Acknowledgements**

This project has been funded by the DFG project Su 121/2. We also thank the Fonds der Chemischen Industrie and the DFG research training group 782 (www.pcgg.de) for support, N. Lütttschwer for developing the heated nozzle setup which was used to vary the cluster concentrations, and S. Montero for valuable early advice on Raman jet spectroscopy.

**References**