Rotational spectroscopy and dipole moment of cis-cis HOONO and DOONO

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I. INTRODUCTION

The primary loss mechanism for HO$_4$(OH+HO$_2$) and NO$_4$(NO+NO$_2$) radicals in the atmosphere is the three-body radical-radical association reaction,

$$\text{OH} + \text{NO}_2 + M \rightarrow \text{HNO}_3 + M.$$  (1)

Knowledge of the rate constant for this reaction is critical to accurate modeling of atmospheric chemistry since catalytic HO$_4$ and NO$_4$ reaction cycles regulate ozone concentrations in the upper troposphere and stratosphere, as well as ozone formation and air quality in the lower troposphere. High-level ab initio calculations have identified cis-cis and trans-perp peroxynitrous acid as stable minima on the HOONO potential-energy surface. Experimental measurements of reaction (1) are thus complicated by the existence of multiple HNO$_3$ products,

$$\text{OH} + \text{NO}_2 + M \rightarrow \text{HONO}_2 + M,$$ (1a)

$$\rightarrow \text{cis-cis} \; \text{HOONO} + M \quad (1b)$$

$$\rightarrow \text{trans-perp} \; \text{HOONO} + M. \quad (1c)$$

The formation of the stable nitric acid isomer, $D_D$(HO–NO$_3$) $\sim$ 80 kJ/mol, via reactions (1b) and (1c), regenerates the OH and NO$_2$ radicals due to rapid thermal decomposition. In fact, cis-cis HOONO measurements provide an effective proxy for the total HOONO yield, (1b) and (1c), under atmospheric conditions since a recent kinetics study demonstrated that the trans-perp conformer isomerizes quickly to the more stable cis-cis HOONO (Fig. 1) at atmospherically relevant temperatures. Recent kinetics and spectroscopy experiments have found both the direct and indirect evidence for HOONO production in the OH+NO$_2$ reaction, and the vibrational spectroscopy of HOONO is a subject of continued study. The current best estimate of the HOONO/HONO$_2$ branching ratio is 0.075±0.020 at 295 K and 20 Torr. Recent spectroscopic modeling suggests an upward adjustment of this branching ratio by approximately 25%. Ongoing experiments to determine the temperature and pressure depen-

FIG. 1. Calculated structure of cis-cis HOONO in principal axis system. The molecule is planar, with partial H bonding between the terminal O and H atoms. The total dipole moment vector is shown.
dences of the branching ratio\textsuperscript{14} suggest a larger HOONO/HONO\textsubscript{2} branching ratio under atmospheric conditions, consistent with kinetic modeling predictions.\textsuperscript{5} All experimental evidence point to a significant rate of HOONO formation in the atmosphere, but it has not been detected in the atmosphere to date.

Our previous work\textsuperscript{15} on the pure rotation spectrum of cis-cis HOONO provided a potential means for specific atmospheric identification from balloon, aircraft, or ground-based millimeter and submillimeter spectrometers. An accurate determination of the permanent electric dipole moment is essential to determine the measurement sensitivity required for atmospheric detection or to quantify HOONO concentrations measured in absorption or emission in the laboratory. We have measured Stark shifts of carefully chosen low-\(J\) transitions to obtain\(\mu_a\),\(\mu_b\), and\(\mu_{\text{total}}\).\textsuperscript{5} The results are compared to spectral simulations and \textit{ab initio} calculations for the vibrationally averaged zero-point level. Additionally, we report the rotation spectrum and dipole moment of DOONO as well as the substitution coordinates of the hydrogen atom. These center-of-mass coordinates render the structure calculations \textit{ab initio} structure calculations.

\textbf{II. EXPERIMENTAL METHODS}

The millimeter and submillimeter measurements were carried out at JPL using a 1-m-long glass cell in double-pass configuration, with sources and detectors at one end of the cell and a polarization-rotating rooftop reflector at the opposite end (Fig. 2). The source and detector are mounted at a relative angle of 90\(^\circ\), with a polarized grid at 45\(^\circ\) to pass from the source and reflect to the detector. Specifics of the multipliers and detectors in use on the millimeter and submillimeter spectrometers are given elsewhere.\textsuperscript{16} For the Stark effect measurements, two parallel-plate electrodes are inserted into the flow cell at an effective separation of \(d = 2.594(44)\) cm.

HOONO was generated by reaction of gaseous 70\% \(\text{H}_2\text{O}_2\) in \(\text{H}_2\text{O}\) (FMC Corporation) with solid NOBF\textsubscript{4} (Aldrich). The NOBF\textsubscript{4} solid was placed in a shallow Pyrex boat inside the absorption cell, over which the hydrogen peroxide vapor flowed from a sidearm port. A slow flow achieved through constriction at the pump port allowed the longest duration of HOONO production. Faster flows reduced the amount of observable by-products (primarily HONO\textsubscript{2}, but also \(\text{HO}_2\text{NO}_2\) and BF\textsubscript{2}OH) but increased the required frequency of venting the system to refill the boat. \(\text{D}_2\text{O}\) (ICON Isotopes), \textasciitilde50\% in \(\text{D}_2\text{O}\), was substituted for \(\text{H}_2\text{O}_2\) as the precursor for DOONO. The cell was conditioned with \(\text{D}_2\text{O}\) prior to the DOONO search and discovery. Substantial HOONO was still observable in the deuterated system, perhaps an indication of atmospheric water absorbed in the hygroscopic NOBF\textsubscript{4} sample. In all cases, the vacuum pump valve was adjusted to optimize the flow rate of \(\text{H}_2\text{O}_2(\text{D}_2\text{O}_2)\) for maximum HOONO (DOONO) production.

The low-frequency rotational spectra of HOONO were collected in a supersonic expansion inside the Mark II Flygare-Balle Fourier-transform microwave spectrometer at Caltech.\textsuperscript{17} In these experiments, the NOBF\textsubscript{4} solid is contained behind a wire mesh in a cavity next to the channel of the pulsed valve housing, directly downstream of the poppet. This solid sample holder was designed for the heating of low-volatility solid samples,\textsuperscript{18} but was used in these experiments at room temperature only. Argon carrier gas is bubbled through a 70\% \(\text{H}_2\text{O}_2\) solution to entrain the reactant \(\text{H}_2\text{O}_2\) in the gas phase, and subsequently pulsed through the sample holder and into the Fourier-transform microwave (FTMW) chamber.

\textbf{III. RESULTS AND DISCUSSION}

\textbf{A. Observed spectra and assignment}

All spectral fitting and rotational line simulations were performed using Pickett’s \textit{spfit} program suite.\textsuperscript{19} The DOONO spectrum was predicted by isotopic shifting of the HOONO spectrum. Characteristic spectral signatures were identified within a few hundreds of megahertz of the estimated positions. These transitions were fitted to refine the prediction and the search continued. The transition frequencies were well predicted after two to three iterations of this process.

The submillimeter wave rotational spectroscopy of \textit{cis-cis} HOONO has been expanded from the previous assign-
TABLE I. Fitted cis-cis HOONO and DOONO Hamiltonian parameters. Values in parentheses represent 1σ uncertainties in units of the least significant figure. Transitions below 13–19 GHz have uncertainty of 2 kHz, 20–122 GHz have uncertainty of 40 kHz, 123–640 GHz have uncertainty of 50 kHz, and 641–847 GHz have uncertainty of 70 kHz.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>HOONO</th>
<th>DOONO</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>MHz</td>
<td>21 406.392 52(61)</td>
<td>20 245.015 69(157)</td>
</tr>
<tr>
<td>B</td>
<td>MHz</td>
<td>7 948.055 26(32)</td>
<td>7 913.267 01(72)</td>
</tr>
<tr>
<td>C</td>
<td>MHz</td>
<td>5 791.000 77(28)</td>
<td>5 685.348 13(63)</td>
</tr>
<tr>
<td>−Δ_J</td>
<td>kHz</td>
<td>−8.053 692(223)</td>
<td>−8.089 64(104)</td>
</tr>
<tr>
<td>−Δ_K</td>
<td>kHz</td>
<td>16.034 16(99)</td>
<td>13.857 3(49)</td>
</tr>
<tr>
<td>−Δ_K</td>
<td>kHz</td>
<td>−59.984 12(32)</td>
<td>−47.067(38)</td>
</tr>
<tr>
<td>−δ_J</td>
<td>kHz</td>
<td>−2.472 485(77)</td>
<td>−2.529 099(257)</td>
</tr>
<tr>
<td>−δ_K</td>
<td>kHz</td>
<td>−13.736 24(181)</td>
<td>−13.302 9(39)</td>
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<td>Φ_J</td>
<td>mHz</td>
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<td>−15.36(44)</td>
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<td>Φ_J/4</td>
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<td>165.4(50)</td>
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<tr>
<td>Φ_K</td>
<td>Hz</td>
<td>1.100 5(46)</td>
<td>0.729(192)</td>
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<tr>
<td>φ_J</td>
<td>mHz</td>
<td>−5.280 3(232)</td>
<td>−5.237(142)</td>
</tr>
<tr>
<td>φ_J/4</td>
<td>mHz</td>
<td>−53.36(70)</td>
<td>−54.7(36)</td>
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<tr>
<td>φ_K</td>
<td>mHz</td>
<td>397.7(43)</td>
<td>298(35)</td>
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<tr>
<td>1.5 χ_{uu}</td>
<td>MHz</td>
<td>2.236 1(37)</td>
<td>1.498(283)</td>
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<tr>
<td>1/4(χ_{uu}−χ_{AA})</td>
<td>MHz</td>
<td>−1.926 8(15)</td>
<td>−1.916 3(277)</td>
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<tr>
<td>χ_{ab}</td>
<td>MHz</td>
<td>3.17(147)</td>
<td>3.17</td>
</tr>
<tr>
<td>σ_{aΔ}/no. of lines</td>
<td>kHz</td>
<td>50.6/480</td>
<td>47.5/246</td>
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</table>

*Value fixed to that determined for HOONO.

ment of 225 lines in the 179–640 GHz range, fit with a standard deviation of 48.4 kHz, to a current data set of 480 lines (115 blended lines of 2, 3, or 4 transitions and 174 nonblended lines) in the 13–840 GHz range, fit with a standard deviation of 50.6 kHz. The measured and calculated frequencies and quantum number assignments are found in the JPL millimeter and submillimeter spectral line catalog at http://spec.jpl.nasa.gov/catalog, and the HOONO SPFIT and SPCAT files are included in the supplemental material. Rotational constants and distortion constants determined from the least-squares fit to this extended data set are shown in Table I.

Cis-cis DOONO scans in the range of 80–640 GHz resulted in a data set of 246 lines (54 blended lines of 2, 3, or 4 transitions and 103 nonblended lines), up to J = 42 and K_a = 18 fit with a standard deviation of 47.5 kHz. The measured and calculated frequencies and quantum number assignments of DOONO are also available in the supplemental material in the form of SPFIT and SPCAT files. Spectroscopic constants determined from the least-squares fit to this data set are also shown in Table I.

Figure 3 shows the measured and simulated spectra of HOONO and DOONO near 270 GHz. In the K_a = 21–20 R branch, only the lowest two K_a components are still “bunched,” with K_a = 0, 1 (not shown) collapsed as a degenerate quartet and K_a = 1, 2 split into quartets with characteristic intensity patterns. Both panels of Fig. 3 are 20 MHz wide, showing the larger spread of the asymmetry splitting in HOONO. The DOONO quartet is more compact and a completely separated HONO_2 feature is visible within the 20 MHz window. The simulations of each quartet take into account the dipole component measurements, which are different for HOONO and DOONO due to a small principal axis rotation. These dipole components are described in the next section and Fig. 3 shows the corresponding change in relative intensities of the inner and outer lines in the quartets.

B. Stark effect measurement of dipole moments

The dipole moments of both HOONO and DOONO were determined by examining Stark effect shifts of 10 and 12 rotational transitions, respectively, in the region of 84–110 GHz under weak-field conditions (0 ≤ e ≤ 0.5 kV/cm). The separation between Stark plates in the spectrometer was found to be 2.594 +0.014 /−0.010 BM) cm after calibration (see below). Therefore the maximum applied field strength was e = V/d = 482 V cm⁻¹.

The weak-field method, described previously by Muller et al., measures the second-order Stark shifts of the intensity weighted averages of unresolved M_J Stark components. The shift for an energy level is of the form

$$\Delta E = \epsilon [A + BM_J^2],$$

where A and B are the Stark coefficients and ε is the strength of the electric field. To calculate the shift for a transition, the
\[ \Delta E \] for the two levels are subtracted. For a reliable weak-field measurement, the combined shifts of the individual Stark components of both the upper and lower levels of each of the \( M_J \) substates must be contained within the linewidth of the measurement. This requirement excludes the use of any near-degenerate energy levels that show rapid splitting of the \( M_J \) levels due to the first-order Stark effect.

The use of a rooftop reflector to rotate the polarization of the millimeter beam radiation by 90° before the second pass of the Stark cell ensured that equal contributions from the intensity weighted average of each transition from each \( M_J \) sublevel is a function of the upper and lower state Stark effect coefficients \( A' \), \( A'' \), \( B' \) and \( B'' \). This average was calculated for each component, \( g \) (\( g=a,b \)).

\[ \frac{\Delta \nu}{\epsilon^2} = \left( A'_g - A''_g \right) + \left( B'_g - B''_g \right) \frac{8J(J+1)}{20} \] for \( \Delta J = 0 \),

\[ \frac{\Delta \nu}{\epsilon^2} = \left[ \left( A'_g - A''_g \right) + \left( B'_g - B''_g \right) \frac{J(J+7)}{20} \right] \] for \( J + 1 \leftarrow J \),

\[ \frac{\Delta \nu}{\epsilon^2} = - \left[ \left( A'_g - A''_g \right) + \left( B'_g - B''_g \right) \frac{J(J+7)}{20} \right] \] for \( J \leftarrow J + 1 \). (3)

The Stark field strength, \( \epsilon \), was calibrated to account for plate separation as well as inhomogeneity in the overlap of the quasi-optical millimeter-wave beam and the electric field by measuring several Stark shifts for \( \text{SO}_2[\mu =1.63305(4) \text{D}] \).\(^{32}\) Stark shifts were measured for ten \( \text{SO}_2 \) transitions to yield a corrected plate separation that also inherently calibrated any linear error in the voltage measurement. The transitions were chosen to fall in the same frequency range as those measured for HOONO; this eliminated the need to consider any frequency dependence in the calibration factor. The calibration factor is \( d=2.599(44) \) cm, yielding measurements with 1.7% accuracy at the 1\( \sigma \) level.

The HOONO and DOONO lines were chosen for Stark shift measurements based on predicted signal strength, shifted line shape, and Stark coefficients. A complete list of the 10 HOONO and 12 DOONO lines used for the Stark analysis is given in Table II, with quantum numbers and zero-field frequencies listed for each line. Two different statistical procedures were used to analyze the data to ensure proper treatment of the measurement statistics. Both procedures began with measurements of line center and shifts of the line center as a function of the applied voltage. The zero-field line center was measured before and after measurements with the applied field and the average frequency was used as the origin for the shift calculation. These before and after zero-field measurements differed from each other by less than 15 kHz for each line. In the first statistical method, the Stark shifts for each transition were fit as a function of \( \epsilon^2 \). Significant deviations from linearity occurred when a transition passed out of the weak-field limit. Therefore, measurements for several of the strongest shifts were removed from the analysis to ensure that all data were within the weak-field approximation. The largest Stark shifts included in the dipole moment fitting were up to 400 kHz for HOONO and 140 kHz for DOONO. In method I, the 1/0 slopes (12 for DOONO) from each regression for each transition were used in a nonlinear fit to the dipole moment components.

\[ \frac{\Delta \nu}{\epsilon^2} = C_a \Delta \nu_a + C_b \Delta \nu_b. \] (4)

Fixed values for \( A' \), \( A'' \), \( B' \), and \( B'' \) determined with a unitary dipole component (under this condition \( C_g=\mu_g \) ) were used to calculate the \( \Delta \nu_g \). The coefficients \( C_a \) and \( C_b \) representing the magnitude of each dipole moment component were then varied to minimize the sum of the squared differences of the measured and calculated slope divided by its uncertainty. The weighted fit was necessary because the measured slopes range over several orders of magnitude. Examples of the individual Stark shift regression measurements are shown in Fig. 4. All Stark shift data are available in the supplemental material.\(^{20}\)

To check the method I results, a second independent statistical analysis was performed (method II) in which all 177 measured HOONO Stark shifts (158 measurements for DOONO) were fit simultaneously to the parameters \( C_a \) and \( C_b \) using Eq. (5).

\[ \Delta \nu(\epsilon) = \epsilon^2 C_a \Delta \nu_a + \epsilon^2 C_b \Delta \nu_b. \] (5)

Both procedures produced precise values for \( \mu_a \) and \( \mu_b \) with differences of less than 4% in \( \mu_a \) and less than 2% in \( \mu_b \). Method II weights all transitions only by their inherent center frequency shift and the quality of this measurement, so this method has been chosen as the preferred approach. The resulting dipole moments are shown in Table III. These components are in good agreement (within 3\( \sigma \)) with \( ab \) \( initio \) calculations of the vibrationally averaged components of the dipole moment,\(^{24}\) also shown in Table III.
Spectroscopy of cis-cis HOONO and DOONO

The direction of the electric dipole moment in HOONO can be determined unambiguously from a comparison of the differences in the axis rotation that is apparent from the \( \mu_a \) and \( \mu_b \) components of the dipole moment for HOONO and DOONO. When the principal axis are defined to place the nitrogen atom in the \((-a, +b)\) quadrant and hydrogen in the \((+a, -b)\) quadrant (as in Fig. 1), the negative pole of the dipole vector is oriented towards the \((+a, +b)\) quadrant. This orientation is expected since the H–O bond has the largest electronegativity differential in the molecule, and this bond is roughly parallel to the total dipole moment vector (see Fig. 1). The 1.7% uncertainty (1\( \sigma \)) in the calibration factor \( d \) dominates the overall accuracy of the dipole moment determination.

C. Position of H atom in principal axis frame

The rotational constants for HOONO and DOONO reported in Table I have been converted into moments of inertia, shown in Table IV. The moments of inertia have also been used to determine the substitution coordinates of the hydrogen atom in the principal axis center-of-mass frame of the molecule using the well-known Kraitchman equations.\(^{25,26}\) The experimentally determined center-of-mass H atom coordinates are reported in Table V.

The structural parameters calculated in this way represent a ground-state effective structure \( (r_e) \), which includes any vibrational effects in the ground-state moments of inertia used to determine the structural parameters. This is evidenced by the nonzero out-of-plane root-mean-squared (rms) displacement of the H atom position. In spite of the planarity of cis-cis HOONO in the \( r_e \) structure, zero-point torsional motion results in a nonzero rms displacement of the H atom out of plane.

This experimental H atom position is compared to the \textit{ab initio} calculated H atom position from several calculations in Table V. The ground-state structure of cis-cis HOONO was first calculated by McGrath and Rowland at MP2/6-311G\((d,p)\),\(^{1} \) and later by Tsai \textit{et al.} at CCSD/6-311++G\((d,p)\),\(^{27} \) by Fry \textit{et al.} at CCSD(T)/cc-pVTZ,\(^{6} \) and by Stanton at CCSD(T) atomic natural orbital (ANO).\(^{28} \) This comparison supports the conclusion that high-level CCSD(T) calculations accurately predict the structural parameters of HOONO.

TABLE IV. Cis-cis HOONO and DOONO moments of inertia and inertial defects. Values in parentheses are 1\( \sigma \) uncertainties based on the fitted parameters. Correlations among the parameters are minimal and were ignored.

<table>
<thead>
<tr>
<th></th>
<th>HOONO</th>
<th>DOONO</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{xx} ) (amu ( \AA^2 ))</td>
<td>23.608 791 8(7)</td>
<td>24.963 135(2)</td>
</tr>
<tr>
<td>( I_{yy} ) (amu ( \AA^2 ))</td>
<td>63.585 248(3)</td>
<td>63.864 781(6)</td>
</tr>
<tr>
<td>( I_{zz} ) (amu ( \AA^2 ))</td>
<td>87.269 728(4)</td>
<td>88.891 489(10)</td>
</tr>
<tr>
<td>( \Delta ) (amu ( \AA^2 ))</td>
<td>0.075 688 865(5)</td>
<td>0.063 573 434(10)</td>
</tr>
</tbody>
</table>

TABLE V. Comparison of HOONO experimental and \textit{ab initio} H atom coordinates.

|            | \( |a| \) | \( |b| \) | \( |c| \) |
|------------|-------|-------|-------|
| MP 2/6-311 G\((d,p)\)^\(a\) | 0.637 | 1.269 | 0.000 |
| CCSD/6-311++G\((d,p)\)^\(a\) | 0.597 | 1.183 | 0.000 |
| CCSD(T)/cc-pVTZ^\(d\) | 0.590 | 1.161 | 0.000 |
| CCSD(T)/ANO^\(d\) | 0.535 | 1.159 | 0.000 |
| Experiment | 0.516 | 1.171 | 0.081 |

\(^{a}\)Reference 1.
\(^{b}\)Reference 27.
\(^{c}\)Reference 6.
\(^{d}\)Reference 28.
D. Inertial defect

The out-of-plane rms displacement of each atom results in a nonzero inertial defect, shown for HOONO and DOONO in Table IV. In HOONO, the positive inertial defect decreases upon deuteration. In a number of planar species (H₂O, H₂S, H₂Se, and H₂CO) deuterium substitution increases the (nominally positive) inertial defect due to dominance of in-plane vibrational motions. However, the inertial defect is a balance of in-plane (typically positive) and out-of-plane (typically negative) contributions. The inertial defect for HOONO is smaller than that for HONO₂, indicating more contribution in HOONO from all out-of-plane motions. Cox and Riveros measured inertial defects for a series of nitric acid isotopomers and found the largest change in inertial defect (−0.0089 amu Å²) with deuterium substitution. This decrease in inertial defect for HONO₂ to DONO₂ indicates dominance of H atom out-of-plane motion, relative to other atoms. The same phenomenon applies in HOONO to DOONO, i.e., the large decrease in inertial defect for deuteration substitution (−0.0121 amu Å²) is consistent with larger amplitude out-of-plane motion of hydrogen than in HONO₂.

Calculations of the inertial defects from the ab initio force field[28,30] \[ \Delta(\text{HOONO}) = 0.0954, \Delta(\text{DOONO}) = 0.0840 \text{ amu Å²} \] show similar decrease with deuterium substitution (0.01141 amu Å²) to that observed experimentally. The positive calculated inertial defect indicates the overall dominance of harmonic force field contributions (in plane), while the change in inertial defect upon deuteration substitution is due mainly to the Coriolis (out of plane) components.

E. Nuclear quadrupole coupling constants

The J = 1 spin of the ¹⁴N nucleus allowed us to measure nuclear quadrupole splitting on selected transitions. Many of the millimeter wavelength transitions of both HOONO and DOONO with J < 25 show characteristic quadrupole splitting patterns. The splittings in Q-branch transitions are resolved enough to determine \( \chi_{bb} - \chi_{cc} \) with four significant figures. Furthermore, the high precision measurements attained in the Flygare-Balle Fourier-transform microwave spectrometer helped improve the precision of the nuclear quadrupole coupling parameter, \( \chi_{aa} \), for HOONO.

HOONO has \( C_s \) symmetry in its ground vibrational state, with the average position of each atom lying in the ab plane, leading by symmetry to \( \chi_{bc} = \chi_{ac} = 0 \), but \( \chi_{ab} \neq 0 \). In general, the weak coupling of ¹⁴N nuclear spin to the rotation of the molecule precludes determination of the full nuclear spin-rotation coupling tensor. However, for cis-cis HOONO the 4₁₁ and 3₂₂ energy levels are accidentally nearly degenerate and the off-diagonal quadrupole coupling allows perturbations among the \( F = 2 \), 3 components. A single measured spectral feature, the 3₂₂ ← 2₁₁ transition in the millimeter range, samples this perturbation and has been used to determine \( \chi_{ab} \). Fits which include the \( \chi_{ab} \) term but do not include the 3₂₂ ← 2₁₁ transition experience a divergence of the fit until a completely undetermined \( \chi_{ab} \) value is obtained. The precision of the splitting in this transition dominates the uncertainty in the determination of the principal quadrupole tensor and the determination of the offset angle \( |\theta| = 23^\circ \) (+5, −8), between the principal inertial axis system and the principal quadrupole axes system. Due to the planar symmetry of this species, this angle necessarily lies in the ab plane; however, its sign is not unambiguous without isotopic information.

IV. CONCLUSIONS

This work extends our previous analysis of the rotational spectrum of cis-cis HOONO. Rotational spectra for HOONO have been measured over frequencies that include nearly the entire range of thermally populated energy levels. The \( \mu_a \) and \( \mu_b \) components of the dipole moment have been determined to an accuracy of 3% using a weak-field Stark shift analysis. Low-frequency, low-J measurements have allowed determination of hyperfine splittings in the rotational spectra due to ¹⁴N nuclear quadrupole coupling. These new data enable the search for cis-cis HOONO via atmospheric remote sensing.

Additionally, the use of deuterated reactants has enabled us to identify and analyze the rotational spectrum of DOONO for the first time. These measurements, combined with our HOONO analyses, provide the precise determination of the hydrogen atom coordinates in the principle axis system. A comparison of HOONO and DOONO dipole moments yields the unambiguous determination of the dipole moment vector. Comparisons between experimental and ab initio dipole moments and H atom position in the principal axis frame agree well, indicating that high-level theory accurately characterizes cis-cis HOONO. Analysis of the inertial defect for HOONO and DOONO is consistent with a planar equilibrium structure with significant out-of-plane H atom torsional motion.

ACKNOWLEDGMENTS

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6. J. L. Fry, S. A. Nizkorodov, M. Okumura, C. M. Roehl, J. S. Francisco,
14 M. Okumura (private communication).
20 See EPAPS Document No. E-JCPSA6-124-017603 for the HOONO and DOONO frequencies and assignments deposited as SPFIT and SPCAT files. Any questions on the file format should be directed to the corresponding author, Brian Drouin. Also included are all Stark shift data for HOONO and DOONO. This document can be reached via a direct link in the online article’s HTML reference section or via the EPAPS homepage (http://www.aip.org/pubservs/epaps.html).
24 The ab initio calculations were performed at the CCSD(T) level with an atomic natural orbital basis set. vibrationally averaged components of the dipole moment were calculations via the expression
\[
\langle \mu' \rangle = \mu'_e + \sum_{q} \frac{\partial \mu'}{\partial q_i} (q_i) + \frac{1}{2} \sum_{q} \frac{\partial^2 \mu'}{\partial q_i^2} (q_i^2),
\]
where the first and second dipole derivatives were calculation ab initio, and the expectation values of the normal coordinates were determined using standard second-order perturbation theory. Further details can be found in X. Zhang, M. R. Nimlos, G. B. Ellison, M. E. Varner and J. F. Stanton, J. Chem. Phys., 124, 084305 (2006) where vibrationally averaged dipole moments of HOONO in the ground and all singly excited vibrational states are documented.
28 J. F. Stanton (private communication).