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On the Fluxional Behavior of Dess−Martin Periodinane: A DFT and ^{17}O NMR Study

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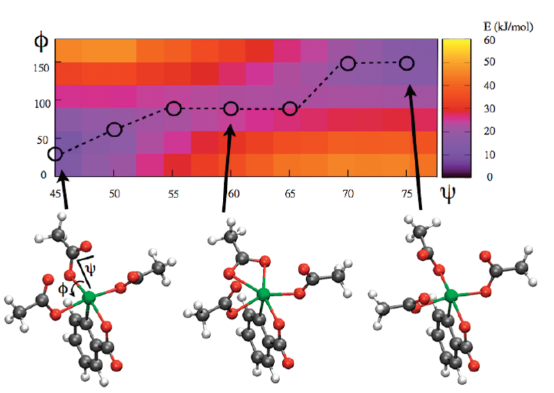

The structure and dynamics of the Dess−Martin periodinane, a I(V) iodobenzene compound widely used in organic synthesis as a mild oxidant, were studied by a combined ^{17}O NMR and DFT calculations approach. The results show that a degenerate [1,3] sigmatropic shift of iodine between the two oxygen atoms of each of the three acetoxy groups occurs in solution. The energy barrier of this process depends on the position of the acetoxy group with respect to the iodoxolone ring and is much lower than the energy barrier observed for similar I(III) compounds.

Over the last years, polyvalent iodine chemistry has experienced a significant growth due to the importance of many derivatives of this class of organic compounds in a large variety of oxidative reactions.[1] Recently, we reported on the solution structure and dynamics of bis(acyloxy)-iodobenzenes and benziodoxolones.[2] Using ^{17}O NMR spectroscopy and density functional theory (DFT) calculations, it was shown that these λ^3 iodanes adopt a T-shaped structure in solution and that the iodine atom experiences a [1,3] sigmatropic shift between the two oxygen atoms of the carboxylic group(s). The energetics and, consequently, the kinetics of this degenerate fluxional process were found to be different for benziodoxolones and bis(acyloxy)iodobenzenes. The carboxylic group involved in the formation of the iodoxolone ring was shown not to be involved in such a [1,3] sigmatropic shift. Dess−Martin periodinane (DMP) and (acetoxy)benziodoxolone have similar structures but DMP, a λ^5 iodane, comprises two additional lateral acetoxy groups (labeled ac′ in Figure 1) bound to the iodine atom. DMP is thus highly suitable to gain a better understanding of the [1,3] sigmatropic shift of hypervalent iodine and, if this fluxional process is present, to ascertain if the previously observed difference between benziodoxolones and bis-(acyloxy)iodobenzenes is maintained, to investigate its dependence on the oxidation number of the iodine atom, and to explore possible stereochemical effects. On the other hand, considering its importance in organic synthesis,[1,3] a deeper characterization of DMP in solution is desirable in itself.

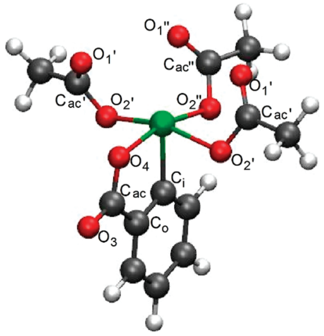

FIGURE 1. Molecular structure and numbering of DMP. The structure shown is the minimum energy structure optimized in vacuo at the PBE0/LANL2DZdp level. Color code: iodine, green; carbon, gray; oxygen, red; hydrogen, white.

The ^{17}O NMR spectrum of DMP recorded in CD_2Cl_2 at 81.3 MHz (600 MHz for ^{1}H) and 40 °C shows four signals with relative integrated intensity in the ratio 1:2:4:1 (Figure 2 and the Supporting Information). This spectrum is indicative of a dynamic process of the acetoxy groups and strongly suggests the occurrence of [1,3] sigmatropic shift processes which are fast on the ^{17}O NMR spectral time scale. Indeed, the spectrum can be explained if the two oxygen atoms of the central acetoxy group are equivalent (320 ppm, 2O) and if the two oxygen atoms of the lateral groups also give rise to a single average signal (332 ppm, 4O), the signals at 234 (1O) and 345 ppm (1O) being due to the nonexchanging oxygen atoms of the iodoxolone ring. Assignment of the ^{17}O NMR signals, based on integral values and DFT calculations (see below), chemical shift (δ), and line width at half height ($\Delta\nu_{1/2}$) values are gathered in Table 1.

It might be argued that equivalence of the oxygen atoms of each of the acetoxy groups could be due to various other

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TABLE 1. Experimental[a] and Computed[b] ^{17}O NMR Data of DMP

	O_4	ac″ ($O_{2''}$, $O_{1''}$)	ac′ ($O_{2'}$, $O_{1'}$)	O_3
exptl δ (ppm)	234	320	332	345
exptl $\Delta\nu_{1/2}$ (Hz)	400	500	450	720
comp. δ (ppm)	234	321 (275, 367)	337 (322, 354) (313, 360)	324

[a] 81.3 MHz, CD_2Cl_2, 40 °C. Chemical shift (δ) and full line width at half height ($\Delta\nu_{1/2}$) data were determined by spectrum deconvolution (see the Supporting Information). $\Delta\nu_{1/2}$ values are corrected for broadening due to apodization (lb = 30 Hz). The errors on $\Delta\nu_{1/2}$ are estimated to be of the order of 15% for O_3 and 10% for the other signals. [b] GIAO chemical shift data calculated at the PBE0/LANL2DZdp/PCM-(CH_2Cl_2) level. The signal of O_4 was chosen for chemical shift referencing (see the Computational Details); the data quoted for the acetoxy groups are the average of the chemical shift values given in parentheses for the corresponding oxygen atoms in the minimum energy structure (see Figure 1).

factors among which are the ionization of DMP and the occurrence of intermolecular exchanges. It is worthwhile noting that for DMP, in contrast to previously studied compounds,[2,4] a chelate bonding mode of all of the acetoxy groups to the iodine atom would not lead, for symmetry reasons, to the equivalence of $O_{1'}$ and $O_{2'}$. Ionization of DMP in solution can be ruled out since acetic acid, present as an impurity in the sample, gives rise to an additional narrow signal (130 Hz) of low intensity observed at 262 ppm (see Figure 2 and the Supporting Information). Intermolecular exchange of the acetoxy groups has been discussed, and excluded, by Dess and Martin.[3b] Furthermore, the addition of some acetic acid has no relevant effect. Indeed, the intensity of the signal at 262 ppm is increased but no significant chemical shift nor line width variations are detected for the ^{17}O NMR signals of DMP (see Figure S3 in the Supporting Information). If it occurs, the chemical exchange between the acetoxy groups bound to DMP and free acetate is very slow on the ^{17}O NMR spectral time scale. The occurrence of a [1,3] sigmatropic shift of iodine with all of the acetoxy groups, similarly to the benziodoxolones and bis(acyloxy)iodobenzenes cases,[2] is the simplest and most likely explanation.

The ^{17}O NMR spectrum of (acetoxy)benziodoxolone recorded in $CDCl_3$ at 40.7 MHz (300 MHz for ^{1}H) shows four signals at 25 °C, indicating slow exchange of the acetoxy oxygen atoms on the NMR spectral time scale.[2] The chemical shift difference between the signals of the acetoxy oxygen pair was measured to be 141 ppm. At 45 °C, these signals were not detected as a consequence of extreme broadening due to coalescence. The activation free energy of the [1,3] sigmatropic shift was estimated to be about 54 kJ/mol, in rather good agreement with in vacuo DFT calculations of the energy barrier found to be 59 kJ/mol.[2] In contrast, with bis(acetoxy)iodobenzene, fast exchange of the acetoxy oxygen atoms was observed at the same experimental conditions and DFT calculations yield 48 kJ/mol as the energy barrier. For DMP in CD_2Cl_2 at 81.3 MHz and 40 °C, the exchange is fast for both the central and lateral acetoxy groups. The $\Delta\nu_{1/2}$ values observed for the acetoxy signals (450 and 500 Hz, see Table 1) are similar and are comparable to the average value of the line width measured for the signals of the nonexchanging oxygen atoms O_4 and O_3 of the iodoxolone ring (560 Hz). This suggests that broadening due to fast transverse nuclear quadrupole relaxation is the major contribution to the observed line width of the acetoxy signals or, in other words, that the exchange of the oxygen atoms within each acetoxy group is very fast on the ^{17}O NMR spectral time scale. Spectra recorded at lower temperatures show significant signal broadening, mainly due to enhanced transverse relaxation as a consequence of increased viscosity, but coalescence was not observed even at −20 °C (see the Supporting Information). Assuming a chemical shift difference between the exchanging oxygen atoms of at least 30 ppm, as suggested by the DFT calculations (see Table 1), this indicates that the activation free energy of the [1,3] sigmatropic shift processes in DMP is considerably lower than 43 kJ/mol (see the Supporting Information). To estimate the energy barriers, a DFT study of DMP was carried out employing the PBE0 functional[5] together with the LANL2DZ basis set[6] extended with polarization (d) and diffuse (p) functions;[6c,d] this theory level was chosen based on its good performance for simulating similar systems.[2] Unless otherwise specified, calculations were conducted in vacuo.

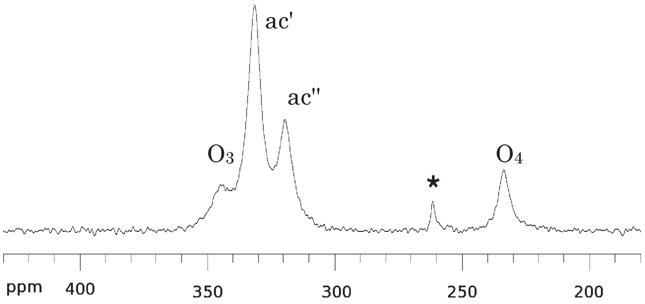

FIGURE 2. ^{17}O NMR spectrum of DMP recorded at 81.3 MHz and 40 °C in CD_2Cl_2 (see the Supporting Information). The asterisk indicates the peak for acetic acid.

The minimum energy structure found for DMP is shown in Figure 1. To the best of our knowledge, no crystal structure is available for this I(V) compound but previous NMR and IR studies are consistent with a square-bipyramidal structure having the covalent bond between iodine and the ipso carbon (the I−C_i bond) as well as an unshared electron pair in apical positions, and four I−O bonds with the ligands in equatorial positions.[3a,7] Other stable conformers, differing in the orientation of the acetoxy group plane with respect to the I−C_i bond, were found but their energy with respect to the most stable conformer implies extremely low population at ambient temperature (see the Supporting Information).

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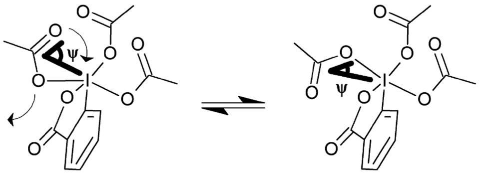
TABLE 2. PBE0/LANL2DZdp Total Energy (kJ/mol) with Respect to the Most Stable Rotamer As a Function of the I−C_{ac}−O_1 Angle (ψ) and C_i−I−O_2−C_{ac} Dihedral (ϕ) for the Lateral and Central Acetoxy Groups[a]

	Lateral Group, ϕ (deg)												Central Group, ϕ (deg)						
ψ (deg)	0	30	60	90	120	150	180	210	240	270	300	330	0	30	60	90	120	150	180
–[b]	2.5	5.4	5.0	14.0	11.5	$\underline{0.7}$	$\underline{2.1}$ ***1.3***	6.7	13.3	6.9	6.9	0.0	31.5	29.7	20.0	16.7	11.2	$\underline{0.3}$ ***0.7***	7.7
75	49.1	44.5	19.3	18.8	14.2	2.4	$\underline{3.7}$	$\underline{7.8}$ ***4.8***	$\underline{13.4}$	16.1	24.2	41.9	51.1	57.2	36.4	24.8	14.8	$\underline{2.0}$ ***2.4***	11.5
70	58.7	55.8	23.3	14.7	15.8	8.3	10.0	13.1	$\underline{14.0}$ ***12.5***	$\underline{11.5}$	23.9	50.4	54.4	62.3	38.7	22.0	$\underline{17.2}$ ***18.8***	$\underline{7.8}$	19.4
65	54.4	54.0	24.4	10.1	17.3	19.0	21.9	23.4	15.7	$\underline{7.9}$ ***5.6***	23.1	48.1	59.0	53.8	35.8	$\underline{18.5}$	$\underline{19.5}$ ***21.6***	18.3	27.1
60	38.7	38.6	23.1	7.1	19.8	33.5	38.9	38.7	19.0	$\underline{7.0}$ ***5.1***	22.4	34.0	43.5	39.0	28.6	$\underline{16.5}$ ***16.2***	22.9	32.6	43.9
55	21.7	22.5	17.8	7.7	23.5	46.9	55.7	49.0	23.3	$\underline{9.8}$ ***9.1***	19.0	18.0	27.0	22.4	$\underline{18.2}$ ***22.8***	$\underline{13.4}$	27.7	46.9	50.2
50	8.9	10.7	8.9	12.1	26.8	48.3	57.2	54.3	23.9	$\underline{15.4}$ ***16.2***	$\underline{12.1}$ ***13.7***	$\underline{5.9}$	14.0	9.0	$\underline{8.7}$ ***11.7***	20.7	31.2	52.7	68.1
45	2.9	5.6	5.1	18.0	26.4	38.5	45.7	41.7	18.5	19.1	7.5	$\underline{0.3}$ ***0.4***	7.4	$\underline{2.3}$	$\underline{3.7}$ ***6.1***	22.1	28.2	43.0	57.1

[a] The minimum energy path for the exchange of the oxygen atoms is underlined. Corresponding data obtained using the PCM model for taking into account the solvent are given in bold and italic. [b] Unconstrained value.

NMR shielding values were calculated on the minimum energy conformation using the GIAO method[8] (see the Computational Details section). O_4 was found to be the most shielded nucleus and, therefore, its chemical shift was set to the lowest experimental value (234 ppm). The resulting predicted chemical shifts are given in Table 1. For the acetoxy groups, if fast exchange of the oxygen atom pairs is considered, the agreement between the experimental and computed data is excellent, making us confident in the adopted theory level. As already observed in a previous study of cyclic compounds,[9] the computed chemical shift of the carbonyl group of the iodoxolone ring (O_3) is significantly lower than the experimental value.

SCHEME 1. Schematic Representation of the [1,3] Sigmatropic Shift of Iodine between the Two Oxygen Atoms of an Acetoxy Group



The study of the [1,3] sigmatropic shift of iodine in DMP followed the same procedure as previously used with bis(acetoxy)iodobenzene and (acetoxy)benziodoxolone,[2] considering that the oxygen exchange necessarily involves the variation of the I−C_{ac}−O_1 angle (see Scheme 1). The potential energy profile was obtained by first varying this I−C_{ac}−O_1 angle (ψ) in steps of 5° between the equilibrium value found in the most stable conformer, ~80°, and 45°. For each constrained value of this angle, a complete scan of the C_i−I−O_2−C_{ac} dihedral (ϕ) was performed by steps of 30°. The structures were optimized leaving all the other geometrical parameters free to vary. The total (electronic + nuclear repulsion) energy difference between the constrained structures and the most stable rotamer is reported in Table 2 (see also the Supporting Information for graphical representations).

Possible solvent effects on the [1,3] sigmatropic shift were investigated by further optimizing selected configurations of the in vacuo minimum energy path employing the polarizable continuum model (PCM).[10] The total PCM energy difference (comprising the electrostatic energy of the molecule in the field of the polarized solvent plus the nonelectrostatic contributions of cavitation, dispersion, and repulsion energies) between the solvated structures and the most stable solvated rotamer is also reported in Table 2. Inclusion of solvent effects using PCM does not lead to large variations of the minimum energy path profiles, although a few kJ/mol increase of the energy maximum is observed for both the lateral and the central acetoxy groups.

The energies involved in the oxygen atoms exchange for both the lateral and central acetoxy groups of DMP are much lower than those observed for the previously studied λ^3 compounds.[2] Indeed, for bis(acetoxy)iodobenzene and (acetoxy)benziodoxolone, the estimated energy barriers were found to be 48 and 59 kJ/mol, respectively. This suggests that the oxidation number of the iodine atom might have a major impact on the energetics of these [1,3] sigmatropic shift processes.

The computational data nicely agree with the fast exchange regime observed experimentally, even at low temperature and high magnetic field, for both the central and lateral acetoxy groups of DMP. Using the calculated chemical shift difference between $O_{1''}$ and $O_{2''}$ of the central acetoxy group (92 ppm) and considering that the activation free energy is between 20 and 25 kJ/mol, the temperature of coalescence at 81.3 MHz (600 MHz for ^{1}H) is estimated to lie

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between −115 and −145 °C. This excludes the experimental observation of the slow exchange regime by solution-state NMR, even at a stronger magnetic field.

Finally, it is worth noting that somewhat higher energies are involved in the oxygen exchange with the central acetoxy group than with the lateral groups (see in vacuo data of Table 2). The previously observed difference between benziodoxolones, for which the I−O bond with the acetoxy group is coplanar with the benzene plane, and bis(acyloxy)iodobenzenes, for which the I−O bonds of the acetoxy groups are nearly perpendicular to the benzene plane, is thus qualitatively retained in DMP.

In conclusion, by combining ^{17}O NMR spectroscopy data and DFT calculations, it is possible to ascertain that the I−O bonds of the Dess−Martin reagent have a fluxional character ascribable to a [1,3] sigmatropic shift of the iodine atom between the two oxygen atoms of each group. This behavior, observable only by ^{17}O NMR, is analogous to that described in our previous study of I(III) organic compounds.[2]

Experimental Section

DMP (97%) was purchased from Sigma-Aldrich and used as received. CD_2Cl_2 (99.6%) was purchased from Euriso-top.

The NMR spectra were recorded on a spectrometer operating at 14.1 T (599.9 MHz for ^{1}H and 81.33 MHz for ^{17}O) equipped with a 5 mm autoX dual broadband probe and temperature regulation. The sample was left to reach equilibrium at the desired temperature within the magnet for at least 30 min before the NMR measurements. Natural abundance ^{17}O NMR spectra were recorded with the improved RIDE (ring down elimination) pulse sequence of Kozminsky et al.,[11] using a 100 μs cawurst adiabatic inversion pulse and the following acquisition parameters: spectral width of about 850 ppm (~69 kHz) centered at 290 ppm, 5 ms relaxation delay, 10 μs (90°) excitation pulse, 10 μs (rof2) preacquisition delay (alfa = 0), 10 ms acquisition time and a number of transients ranging between 1×10^6 and 5×10^6. The receiver ddrtc parameter was optimized to obtain spectra without first-order phase error. The spectra were recorded lock-on without sample spinning. The processing comprised correction of the first 3 points of the Free Induction Decay (FID) by backward linear prediction (see the Supporting Information), exponential multiplication of the FID with a line broadening factor of 30 Hz, zero filling (resulting digital resolution of 4.2 Hz per point), Fourier transform, zero-order phase correction, and baseline correction. The chemical shift scale was calibrated at 25 °C with respect to a sample of pure H_2O used as an external chemical shift reference (0 ppm).

Computational Details

Structure optimization was performed at the DFT level employing the PBE0 functional,[5] a parameter-free hybrid variant of the Perdew, Burke, and Ernzerhof (PBE) generalized gradient functional,[12] as implemented in the commercially available suite of programs GAUSSIAN 03.[13] The effective-core-potential valence basis set LANL2DZ[6] (i.e., D95V[6a] basis set for the first row elements and the Los Alamos ECP plus DZ on iodine[6b]) extended with polarization (d) and diffuse (p) functions[6c,d] was employed for all atoms. Numerical integration was performed using a pruned grid having 99 radial shells and 509 angular points per shell. Unconstrained geometry vibrational analysis was carried out at the same level of theory to check the character of the stationary points. To find the global minimum, the geometry of the studied compound was optimized starting from several conformations, constructed with the freely available program Molden,[14] differing in the value of the dihedral angle around the I−O bonds.

Selected atomic configurations were further optimized mimicking the solvent with a polarizable continuum model (PCM),[10] using the current implementation[10a] in Gaussian 03, performing a reaction field calculation using the integral equation formalism IEF-PCM.[10b−d] Further details on PCM optimization are given in the Supporting Information.

NMR shielding was calculated on the PCM optimized geometry using the gauge-including atomic orbital (GIAO) method[8] at the same theory level adopted for the geometry optimization. Calculated absolute shielding data, σ, were converted into the usual chemical shift scale employing the equation $\delta = \sigma_{\mathrm{ref}} + \delta_{\mathrm{ref}} - \sigma$, where σ_{ref} and δ_{ref} are respectively the calculated absolute shielding and the experimental chemical shift of a chosen reference. An oxygen atom of the studied molecule (O_4) was selected for chemical shift referencing since it was shown that the use of a chemically similar atom as reference cancels systematic errors and permits good chemical shift predictions.[9]

Graphics of molecular models were generated using the freely available VMD[15] software.

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Supporting Information Available: ^{17}O NMR spectra measurements and spectrum deconvolutions and additional computational details, Cartesian coordinates, and total energies of the computed geometries. This material is available free of charge via the Internet at http://pubs.acs.org.

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