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Conformation Analysis

Pseudorotational Landscape of Seven-Membered Rings: The Most Stable Chair and Twist-Boat Conformers of ε-Caprolactone

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Abstract: The conformational landscape and ring-puckering properties of ε-caprolactone have been analyzed by using microwave spectroscopy and quantum chemical calculations. Two conformers were detected in a supersonic jet expansion, the most stable form being a chair containing the ester group in its rectangular flap. This conformation benefits from reduced CH_2 bond eclipsing and angle strain, while π-electron delocalization in the ester group is increased. The derived effective structure of the chair form satisfactorily agrees with the calculated near-equilibrium structure. A twist-boat conformer was also identified (9.4 kJ mol^{-1} higher in energy at CCSD(T)/aug-cc-pVTZ level), and was located in the boat-twist-boat pseudorotation cycle of the seven-membered ring. Three other low-energy conformers were investigated and characterized in terms of the four puckering coordinates of the seven-membered ring. Potential interconversions in the four-dimensional conformation space are also discussed.

Introduction

The conformational properties of cycloalkanes become increasingly complex with increasing ring sizes. For an *N*-membered ring, there are $N-3$ large amplitude vibrations that lead to nonplanar (puckered) ring conformations. Cremer and Pople derived that the $N-3$ dimensional conformation space can be partitioned into two-dimensional pseudorotational spaces for odd-membered rings and an additional inversion space for even-membered rings.[1,2] However, in addition to pseudorotation, inversion and semi-inversions, there are other interconversions between these subspaces. For this reason, the conformational changes of seven-membered rings represent instructive examples of molecular flexibility and complexity, with chemical implications for larger molecules containing these motifs.

The prototype of a seven-membered ring is cycloheptane, which has been investigated by force field[3–6] and, later, ab initio[7–9] theoretical methods. The ab initio (and partly the force field) are consistent with the experimental results.[4,5,10,11] Following Cremer, boat (B) and twist-boat (TB) forms of cycloheptane undergo free pseudorotation in a two-dimensional subspace of the four-dimensional conformation space, accordingly called the B-TB pseudorotation subspace. Pseudorotation is slightly hindered by a barrier of 1.8 kJ mol^{-1} in the chair–twist-chair (C–TC) subspace.[7] An energetically more favorable pseudorotation path results from a linear combination of B–TB and C–TC forms. Bocian and co-workers assumed constant puckering amplitudes (q_2, q_3, with $c \cdot q_2 \gg q_3$; c being a scaling factor to avoid a reentrant torus) and presented the conformational surface of cycloheptane as a torus surface. The most favorable pseudorotation path under these constraints describes a helical path winding around the torus.[3,5] A number of other seven-membered rings have been investigated, including cycloheptene,[12,13] oxacycloheptanes,[5,9] ε-caprolactam,[13] and cycloheptatriene and its analogues.[14] Other attempts were made to visualize conformations and interconversions in the four-dimensional conformation space of the seven-membered ring by using various simplifications.[15–17] However, the description based on the normalized Cremer–Pople (CP) puckering coordinates, which describes the seven-membered ring in terms of basis conformations, has turned out to be the most systematic.[7,16,18]

Although there are many structural investigations of seven-membered rings, a systematic exploration of their conformational space in terms of the CP or general curvilinear coordinates[19] backed up by appropriate experimental investigations

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is missing so far. A range of experimental techniques have been used to study the conformational landscapes of moderately-sized rings, but with the exception of electron diffraction (GED),[10] they all operate on condensed phases, so a quantitative comparison with quantum chemical calculations requires canceling the intermolecular forces and crystal packing effects. Hence, new high-resolution spectroscopic techniques are gaining pivotal importance.[20] In particular, the recent introduction of chirped-excitation broadband microwave (MW) spectroscopy techniques[21–23] offers broadband multiplexing capabilities and has dramatically expanded the molecular complexity amenable to rotational resolution studies.[24] Here, we use a combination of supersonic-jet techniques and broadband MW spectroscopy to examine the structural properties of the seven-membered ring of ε-caprolactone.

ε-Caprolactone introduces an oxygen atom and the ester sp^2-hybridized C atom into the seven-membered ring, but retains much of the conformational flexibility of cycloheptane, making interesting a comparison with the prototype molecule. A recent conformational search by Groenewald and Dillen[13] extended previous force field,[25] density functional theory (DFT), and Gaussian 3 (G3) studies,[26] and suggested five stable conformers with relative energies lower than 21 kJ mol^{-1} and interconversion barriers up to 67 kJ mol^{-1}. The objectives of our investigation were to verify these predicted conformers by a two-pronged approach combining modern MW spectroscopy[21–23,27] with high accuracy quantum chemical calculations based on a systematic use of the CP puckering coordinates. Especially, it has to be clarified which forms are experimentally detectable, how they can be accurately described, and what electronic effects lead to their stabilization. Previous studies of ε-caprolactone are limited to an old microwave work[28] and some X-ray diffraction analysis of derivatives.[29]

Results and Discussion

Microwave spectrum

The microwave spectrum of caprolactone was analyzed in the 6–18 GHz region. A spectral section around 18 GHz is shown as an example in Figure 1. Inspection of the most intense transitions resulted in the assignment of the rotational spectrum of the species identified as a chair conformation in the previous MW work.[28] A second, previously unknown conformer was later identified in the spectrum. Final rotational parameters derived with a Watson semirigid rotor Hamiltonian[30] (S-reduction) are shown in Table 1. To elucidate the molecular structure, a spectral search was accomplished for all seven isotopic species corresponding to the monosubstituted ^{13}C and ^{18}O atoms in the ring skeleton of the lactone, which could be detected in natural abundance (0.2–1%) for the most intense conformation. The rotational parameters for the detected isotopologues are collected in Table S1 (see the Supporting Information). No other caprolactone species could be assigned in the spectrum with reasonable integration times. The transition frequencies for all caprolactone species are shown in Tables S2–S10 (see the Supporting Information). The structural analysis used substitution[31] and effective[32] procedures. The resulting structure for the most stable caprolactone species is shown in Table 2.

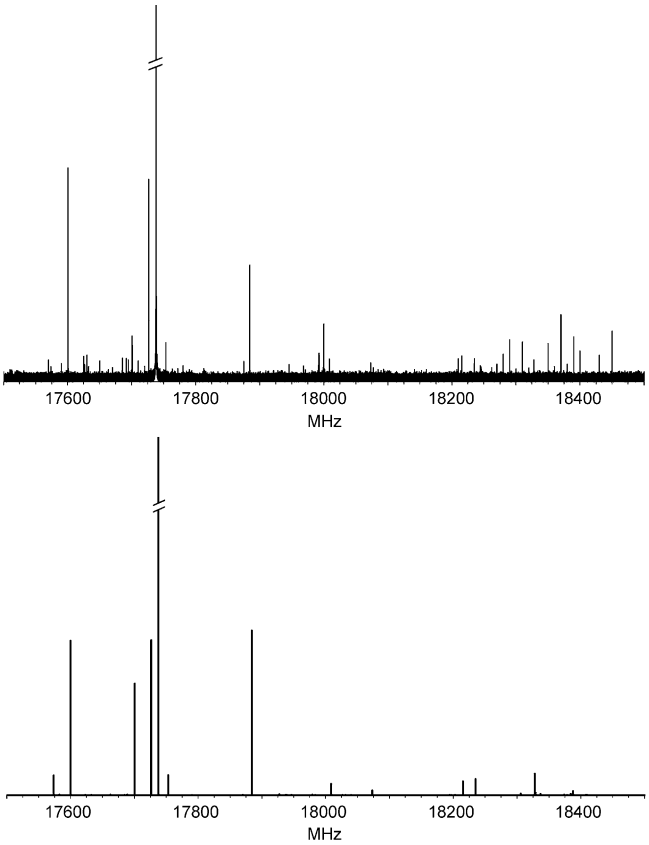

Figure 1. A 1 GHz section of the microwave spectrum of ε-caprolactone. The upper panel is the experimental spectrum (101,842 averaging cycles). The lower panel is an ab initio simulation.

Table 1. Experimental rotational parameters of ε-caprolactone.

	Conformer 1[a]	Conformer 2[a]
A_0 [MHz][b]	3201.298660(86)	3022.0866(25)
B_0 [MHz]	1920.553798(40)	2022.40662(55)
C_0 [MHz]	1348.768960(82)	1508.66893(42)
D_J [kHz]	0.25053(55)	0.3326(34)
D_{JK} [kHz]	−0.77745(55)	−0.774(16)
D_K [kHz]	2.0498(13)	[0.][d]
d_1 [kHz]	−0.06473(14)	−0.0437(35)
d_2 [kHz]	−0.004930(47)	0.0024(20)
N[c]	43	20
σ [kHz]	0.9	1.7

[a] Standard errors in parentheses in units of the last digit. [b] Rotational constants (A_0,B_0,C_0) and Watson's S-reduction centrifugal distortion constants (D_J, D_{JK}, D_K, d_1, d_2) in the vibrational ground-state. [c] Number of fitted transitions (N) and microwave standard deviation (σ) of the fit. [d] Fixed to zero.

Table 2. Structure of the most stable C^{5+} chair conformation of ε-caprolactone.

	r_0 [a],[b]	r_s [b]	r_e
$r(O^1–C^2)$ [Å]	1.360	1.333(22)[c]	1.360
$r(C^2–C^3)$ [Å]	1.517	1.538(29)	1.517
$r(C^3–C^4)$ [Å]	1.540	1.523(10)	1.540
$r(C^4–C^5)$ [Å]	1.529	1.535(10)	1.529
$r(C^5–C^6)$ [Å]	1.529	1.525(15)	1.529
$r(C^6–C^7)$ [Å]	1.525	1.530(8)	1.525
$r(C^7–O^1)$ [Å]	1.432[c]	1.429(14)	1.437
$r(C^2–O^8)$ [Å]	1.210		1.210
$\measuredangle(O^1\text{-}C^2\text{-}C^3)$ [°]	119.08(55)	119.1(15)	118.6
$\measuredangle(C^2\text{-}C^3\text{-}C^4)$ [°]	113.87(25)	113.5(14)	112.6
$\measuredangle(C^3\text{-}C^4\text{-}C^5)$ [°]	113.62(32)	113.2(15)	113.4
$\measuredangle(C^4\text{-}C^5\text{-}C^6)$ [°]	114.45(41)	114.0(12)	114.2
$\measuredangle(C^5\text{-}C^6\text{-}C^7)$ [°]	115.17(59)	113.9(15)	114.4
$\measuredangle(C^6\text{-}C^7\text{-}O^1)$ [°]	113.40(80)[c]	113.2(11)	113.3
$\measuredangle(C^7\text{-}O^1\text{-}C^2)$ [°]	121.41(65)[c]	121.5(19)	120.9
$\measuredangle(C^3\text{-}C^2\text{-}O^8)$ [°]	122.80(28)[c]	121.27(90)	122.8
$\tau(O^1\text{-}C^2\text{-}C^3\text{-}C^4)$ [°]	−64.4(19)	−65.5(44)	−70.4
$\tau(C^2\text{-}C^3\text{-}C^4\text{-}C^5)$ [°]	81.55(53)	81.1(47)	81.6
$\tau(C^3\text{-}C^4\text{-}C^5\text{-}C^6)$ [°]	−59.05(13)	−60.6(10)	−58.6
$\tau(C^4\text{-}C^5\text{-}C^6\text{-}C^7)$ [°]	57.47(15)	59.8(35)	59.4
$\tau(C^5\text{-}C^6\text{-}C^7\text{-}O^1)$ [°]	−81.8(13)[c]	−83.1(32)	−83.6
$\tau(C^6\text{-}C^7\text{-}O^1\text{-}C^2)$ [°]	70.9(10)[c]	71.9(44)	68.8
$\tau(C^7\text{-}O^1\text{-}C^2\text{-}C^3)$ [°]	−2.2(16)[c]	4.6(28)	1.5
$\tau(C^4\text{-}C^3\text{-}C^2\text{-}O^8)$ [°]	111.38(74)		108.2

[a] Substitution, effective and equilibrium (MP2) structures denoted respectively; r_s, r_0 and r_e. [b] Standard errors in units of the last digit. [c] Derived values.

Pseudorotational landscape

A description of the puckering coordinates appropriate for seven-membered rings is given in the Supporting Information. Briefly, the four-dimensional space can be described by the CP hypercyclindrical coordinates[1] q_2, ϕ_2 and q_3, ϕ_3, where the puckering amplitude q and the phase angle ϕ span a two-dimensional ring-pseudorotation space, which represents the location of an infinite number of conformations of a specific puckering type. By using the mean plane as a reference plane, there are four basis conformations for cycloheptane: the C_s-symmetrical boat (B; $q_2 > 0$, $\phi_2 = 0°$, atom C1 in the symmetry plane above (+) the mean plane: B^{1+}), the C_2-symmetrical twist-boat (TB; $q_2 > 0$, $\phi_2 = 90°$, atom 1 on the C_2 symmetry axis, atom 2 below (−) the mean plane, clockwise numbering of the ring atoms: TB^{1-}), the C_s-symmetrical chair (C; $q_3 > 0$, $\phi_3 = 0°$: C^{1+}), and the C_2-symmetrical twist-chair conformation (TC; $q_3 > 0$, $\phi_3 = 90°$: TC^{1-}).[7,18] For cycloheptane, there are 14 B and 14 TB conformations at $\phi_2 = 2n \times 180/14$ and $(2n+1) \times 180/14$, respectively ($n = 0, 1, \ldots, 13$), and similarly 14 C and 14 TC conformations at the corresponding ϕ_3 values, which can be identified by denoting the atom that takes the position in the symmetry plane (up or down) or on the C_2-axis (+ the up/down position of atom 2). These 28 forms are shown for the B–TB and the C–TC pseudorotation cycles of caprolactone in Figure 2 and Figure 3, respectively (replacement of the O atom by C reinstalls the situation of cycloheptane). Alternatively, the conformational space can be described by the hyperspherical coordinates Q, θ, ϕ_2, ϕ_3, where Q is the total puckering amplitude of the seven-membered ring ($Q = (q_2^2 + q_3^2)^{1/2}$) and $\theta_2 = \arctan(q_2/q_3)$ describes the mixing of conformers from the two different pseudorotational cycles.

We show in Table 3 the CP coordinates for the five lowest-lying conformers of caprolactone. The predicted most stable caprolactone conformation is the C^{5+}/C^{5-} form depicted in Figure 4, in which the ester group is located in the rectangular flap of the chair. This species has several stabilizing effects: 1) The destabilizing CH_2CH_2 eclipsing typical of C^{1+}, C^{7+}, etc. is avoided. 2) The COC and OC(=O)C angles can widen to 118.7 and 117.2°, respectively, thus relieving ring strain (the sp^2-hybridized C(=O) prefers an angle close to 120°). 3) A planar ester group facilitates $p\pi(O) \rightarrow \pi^*(C{=}O)$ electron delocalization, leading to $O^1{=}C^2$ bond shortening (from 1.376 to 1.260 Å) and $C^2{=}O$ bond lengthening (from 1.207 to 1.210 Å). These steric/elec-

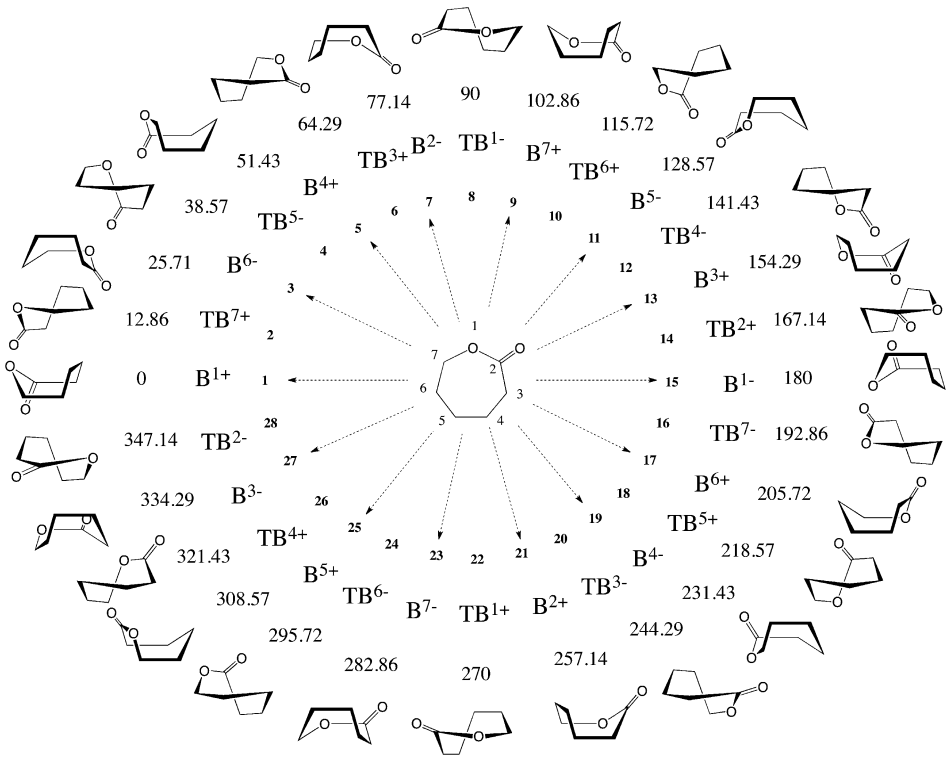

Figure 2. Boat-twist/boat pseudorotation cycle of ε-caprolactone shown in the q_2-ϕ_2 space of the seven-membered ring. For a constant value of the puckering amplitude q_2, the puckered ring is given for ϕ_2 phase angles defined by n 180/14 with $n = 0, 1, \ldots, 13$.

Table 3. Ab initio (MP2 and CCSD(T)) predictions for the most stable conformations of ε-caprolactone.

	C^{5+} chair	TB^{6+} twist-boat	TC^{7-} twist-chair	TC^{3+} twist-chair	TB^{5-} twist-boat
A_e [MHz][a]	3178.4	3018.9	2657.3	2748.2	3352.4
B_e [MHz]	1935.1	2032.3	2430.6	2295.0	1851.7
C_e [MHz]	1359.6	1522.4	1623.1	1575.8	1340.1
D_J [kHz]	0.30	0.31	0.52	0.58	0.15
D_{JK} [kHz]	−1.06	−0.51	−0.54	−0.60	0.10
D_K [kHz]	2.49	1.20	0.47	0.78	0.72
d_1 [kHz]	−0.078	−0.042	−0.13	−0.094	−0.011
d_2 [kHz]	−0.0041	−0.0086	−0.024	−0.039	−0.0043
$\lvert\mu_a\rvert$ [D]	4.56	4.09	2.81	2.71	4.93
$\lvert\mu_b\rvert$ [D]	0.61	1.12	0.64	1.14	0.64
$\lvert\mu_c\rvert$ [D]	1.55	2.06	0.47	0.34	0.09
$\lvert\mu_{TOT}\rvert$ [D]	4.86	4.72	2.92	2.95	4.98
q_2 [Å]	0.486	1.162	0.598	0.594	0.880
ϕ_2 [°][b]	126.8	118.4	195.7	244.5	42.5
q_3 [Å]	0.650	0.028	0.664	0.656	0.380
ϕ_3 [°]	101.1	209.7	241.0	145.1	192.0
Q [Å]	0.811	1.163	0.894	0.885	0.959
θ [°]	36.8	88.6	42.0	42.2	66.6
decom-	64.2% C^{6+}	99.9% TB^{6+}	55.2% TC^{5-}	54.9% TC^{7-}	84.3% TB^{5-}
position	35.8% B^{5-}	0.1% C^{4+}	44.8% TB^{7-}	45.1% TB^{3-}	15.7% TC^{6-}
ΔE^{MP2}[c]	0.0	9.08	17.24	20.38	22.84
ΔG^{MP2}	0.0	8.49	17.82	20.38	21.42
$\Delta E^{CCSD(T)}$	0.0	9.41	19.96	22.09	22.26
$\Delta G^{CCSD(T)}$	0.0	8.83	20.54	22.09	20.75

[a] Rotational parameters as defined in Table 1. Electric dipole moment components in the principal inertial axes (1 D $\approx$ 3.336×10^{-3} Cm). [b] Definition of ϕ_2 and ϕ_3 in Figures 2 and 3. [c] CCSD(T)/aug-cc-pVTZ at MP2/6-311++G(d,p) geometries [in kJ mol^{-1}]. Thermochemical and entropic corrections for free energy differences calculated at the MP2 level of theory.

tronic factors lead to the 9.2 to 22.2 kJ mol^{-1} higher stability of C^{5+} and its inverted counterpart C^{5-} compared with the four other conformers investigated in Table 3.

It is interesting to note that C^{5+} is the result of a linear combination of 64% C^{6+} and 36% B^{5-} (see Figures 2 and 3); that is, a superposition of a C and a B form, which has two effects. First, it flattens the triangular flap and steepens the rectangular flap of the chair without increasing the extent of CH_2CH_2 eclipsing. Secondly, it shifts the ester group by one position, thus converting a C^{6+} into a C^{5+} conformation. Furthermore, the total puckering amplitude Q increases from that of a pure C form (0.650 Å) to $Q=0.811$ Å, which leads to increased CH staggering (lowest HCCH dihedral angle: 40°).

The second most stable conformational pair predicted is located in the B-TB pseudorotational space and corresponds to TB^{6+}/TB^{6-} (see Figure 2). It has a relative energy of 9.4 kJ mol^{-1} ($\Delta G=8.5$ kJ mol^{-1}, Table 3) and the total puckering amplitude Q is 1.163 Å, which is thereby similar to that of cycloheptane (1.161 Å).[7] A θ value of 88.6° reveals that TB^{6+} is only slightly distorted (0.1%). This conformation also enables the ester group to lie approximately in a plane ($\measuredangle C^7O^1C^2C^3=-6.6°$; $\measuredangle C^7O^1C^2=118.7°$, $\measuredangle O^1C^2C^3=117.2°$), which has similar stabilizing effects as for the C^{5+}/C^{5-} pair (reduced strain, pπ(O)→π*(C=O) delocalization). However, CH bond staggering is less developed than for the latter form.

These results are in line with the results of previous quantum chemical investigations of caprolactone[13,26] or cycloheptane.[7] For the latter molecule, Cremer found that B and TB forms have the same puckering amplitudes of 1.163 Å and undergo almost free pseudorotation. The ideal C and TC forms have 28.5 and 30.1 kJ mol^{-1} higher energies and smaller puckering amplitudes ($q_3=0.664$ Å), which results from increased CH_2 group eclipsing with increased puckering, in contrast to the B-TB family for which increased puckering leads to a reduction of CH_2 group eclipsing. However, the C (and TC) form can be stabilized by 40.6 (46.4) kJ mol^{-1} relative to the B (TB) form by an admixture of 32% B (39% TB) form. In a similar way, the C^{5+}/C^{5-} forms of caprolactone benefit from an admixture of C and B puckering.

There is a discrepancy between our results and those of Groenenwald and Dillen[13] in the case of the TB^{6+} form. The latter authors erroneously describe the second most stable conformer as the "B5" form ($\phi_3=128.57°$, Figure 2), whereas in view of a ϕ_3 value of 118.4° (Table 3), this is clearly a 21% perturbed TB^{6+} form ($\phi_3=115.72°$, Figure 2). The advantage of the TB^{6+} form is that a somewhat larger $O^1C^2(=O)C^3$ bond angle can be accommodated, thus decreasing ring strain.

An admixture of TC and TB forms is found for conformations TC^{3+} (55% TC^{7-} + 45% TB^{3-}) and TC^{7+} (55% TC^{5-} + 45% TB^{7-}), which are 22.1 and 20.0 kJ mol^{-1} higher in energy than C^{5+} (Table 3). According to the calculated ΔG values, these conformers should not be populated at room temperatures. TC^{3+} and TC^{7+} are located on the energetically most likely C-TC pseudorotation itinerary, which, for cycloheptane as well as caprolactone, is the helical path winding around the torus presentation of the conformational surface as first suggested by Strauss and co-workers on the basis of force field calculations. These results were later confirmed by Cremer[7] on the basis of ab initio Hartree–Fock complete geometry optimizations in terms of puckering coordinates.[3–5] There is a TB^{5-} form with 15.7% TC^{6-} character located on an interconversion path from B-TB to C-TC space (see Table 3), which has the highest relative energy (22.3 kJ mol^{-1}, Table 3) of the five conformers investigated.

The conformational assignment of the species detected in the experiment relied on the rotational constants and, for the most intense conformer, on the experimental substitution coordinates and derived structure (Table 2). Comparison of the measured rotational constants of Table 1 with the predictions in Table 3 reveals that the first conformer experimentally observed corresponds to the C^{5+}-chair, which occupies the global minimum of the conformational surface of caprolactone. We note that the ground-state rotational constants (A_0, B_0, C_0) cannot be identical to the equilibrium values (A_e, B_e, C_e). However, deviations are in the 0.7–0.8% range, which can be expected for identical conformers. The same holds for the comparison of the experimentally-based effective (r_0) and substitution (r_s) structures and the calculated equilibrium (r_e) values in Table 2, for which the r_0 bond lengths especially facilitate the identification of conformer 1 as the being identical to C^{5+}/C^{5-}.

The r_0-structure leads to the following puckering coordinates: $q_2=0.475$ Å, $\phi_2=133.5°$, $q_3=0.638$ Å, and $\phi_3=103.5°$.

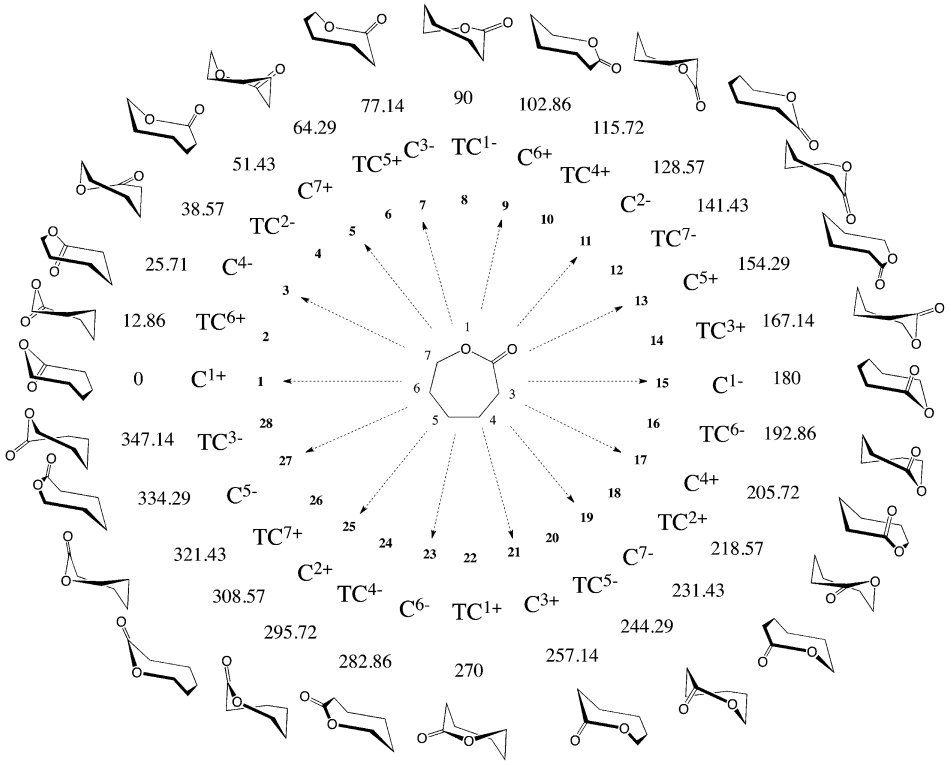

Figure 3. Chair-twist/chair pseudorotation cycle of ε-caprolactone shown in the q_3-ϕ_3 space of the seven-membered ring. For a constant value of the puckering amplitude q_3, the puckered ring is given for ϕ_3 phase angles defined by n 180/14 with $n=0, 1, \ldots, 13$.

values. Despite these small differences, the same B^{5-} and C^{6+} forms mix in the same way as is reflected by a θ value of 36.7° (36% B^{5-} and 64% C^{6+}). The r_s-structure deviates somewhat more, although it is closer in the puckering amplitudes q_3 and Q: $q_2=0.463$ Å, $\phi_2=130.3°$, $q_3=0.652$ Å, $\phi_3=103.0°$, $Q=0.800$ Å, $\theta=35.4°$ (33.5% B^{5-} and 66.5% C^{6+}). In summary, the r_0-, r_s-, and r_e-structures describe the same chair conformer.

The second conformer was identified as the TB^{6+}/TB^{6-} form in view of the agreement between measured and calculated rotational constants (Table 1 and Table 3; average deviation: 0.4%). The lack of other conformations in the jet-cooled spectrum should be associated either to thermal depopulation or to eventual conformational relaxation in the jet.

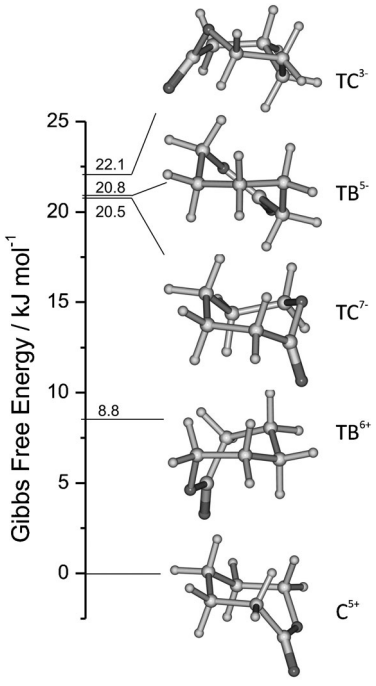

Figure 4. The five most stable conformers of ε-caprolactone according to CCSD(T)/aug-cc-pVTZ calculations.

The total puckering amplitude $Q=0.795$ Å is 2% smaller than the calculated value, and this is also true for the individual q_m

Conclusion

In this work, the two most stable conformers of ε-caprolactam were identified by a two-pronged approach involving state-of-the-art microwave measurements and high-accuracy quantum chemical calculations. The most stable species of caprolactone are the chair forms C^{5+}/C^{5-} and the twist-boat forms TB^{6+}/TB^{6-} (Figure 4), with the latter conformer pair being 9.4 kJ mol^{-1} less stable according to CCSD(T) calculations. The C^{5+}/C^{5-} conformer gains its stability from a mixing of C^6 and B^5 conformations, which leads to a flattened chair form having the ester group in the rectangular flap of the chair, thus guaranteeing increased staggering, reduced ring strain, and π-electron delocalization. There is an excellent agreement between the measured and calculated rotational constants as well as the experimental (r_0) and calculated (r_e) structures in the case of the conformer pair C^{5+}/C^5. Additionally, the TB^{6+}/TB^{6-} pair was unambiguously identified by the rotational constants. Despite incorporation of the ester group into the seven-membered ring, there are close conformational relationships between caprolactone and cycloheptane: For both ring molecules, the most stable conformer is located on the helical pseudorotation cycle connecting the B-TB and C-TC conformation spaces. The puckering amplitude of the TB forms of caprolactone and cycloheptane are almost identical. Differences between the ring molecules result from the different CH_2—CH_2 eclipsing situations (required for caprolactone), which leads to the C and TC forms having somewhat higher puckering amplitudes.

The conformational analysis carried out in this work illustrates the advantages of employing puckering coordinates (or

in general curvilinear coordinates) and suggests that the conformation space of seven-membered and larger ring molecules should be systematically explored by using these coordinates for both analytical energy gradient and analytical energy hessian.[19] Further experiments on other seven-membered rings will follow to help understand fully the intramolecular dynamics of these cycloalkanes.

Experimental Section

Experimental and theoretical methods are fully detailed in the Supporting Information. The molecule was probed in a supersonic jet expansion using a broadband Fourier transform microwave (FT-MW) spectrometer design that implements the in-phase/quadrature-phase-modulation pulse-acquired coherence technique (IMPACT).[21–23] Additional measurements used a Balle-Flygare-type FT-MW spectrometer using a multipass Fabry-Pérot resonator with a COBRA (coaxially oriented beam-resonator axes) configuration.[27] The theoretical study combined ab initio calculations and a comprehensive survey of the pseudorotational landscape using Cremer–Pople coordinates.[1–2]

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[1] D. Cremer, J. A. Pople, *J. Am. Chem. Soc.* **1975**, *97*, 1354.
[2] D. Cremer, K. J. Szabó, *Conformational Behaviour of Six-Membered Rings. Analysis, Dynamics and Stereoelectronic Effects in Methods in Stereochemical Analysis* (Ed.: E. Juaristi), Chapter 3, pp. 59 – 145, **1995**.
[3] D. F. Bocian, H. M. Pickett, T. C. Rounds, H. L. Strauss, *J. Am. Chem. Soc.* **1975**, *97*, 687.
[4] D. F. Bocian, H. L. Strauss, *J. Am. Chem. Soc.* **1977**, *99*, 2866.
[5] D. F. Bocian, H. L. Strauss, *J. Am. Chem. Soc.* **1977**, *99*, 2876.
[6] P. M. Ivanov, E. Osawa, *J. Comput. Chem.* **1984**, *5*, 307.
[7] D. Cremer, *J. Phys. Chem.* **1990**, *94*, 5502.
[8] K. B. Wiberg, *J. Org. Chem.* **2003**, *68*, 9322.
[9] F. Freeman, J. H. Hwang, E. H. Junge, P. D. Parmar, Z. Renz, J. Trinh, *Int. J. Quantum Chem.* **2008**, *108*, 339.
[10] J. Dillen, H. J. Geise, *J. Chem. Phys.* **1979**, *70*, 425.
[11] N. Verdal, J. J. Wilke, B. S. Hudson, *J. Phys. Chem. A* **2006**, *110*, 2639.
[12] a) N. L. Allinger, J. T. Sprague, *J. Am. Chem. Soc.* **1972**, *94*, 5734; b) M. K. Leong, V. S. Mastryukov, J. E. Boggs, *J. Mol. Struct.* **1998**, *445*, 149.
[13] F. Groenewald, J. Dillen, *Struct. Chem.* **2012**, *23*, 723 – 732.
[14] D. Cremer, B. Dick, D. Christen, *J. Mol. Struct.* **1984**, *110*, 227.
[15] P. J. de Clercq, *J. Org. Chem.* **1981**, *46*, 667.
[16] a) F. H. Allen, J. A. K. Howard, N. A. Pitchford, *Acta Crystallogr. B* **1993**, *49*, 910 – 928; b) F. H. Allen, J. A. K. Howard, N. A. Pitchford, J. G. Vinter, *Acta Crystallogr. B* **1994**, *50*, 382 – 395.
[17] S. Goto, K. Komatsu, H. Terada, *Bull. Chem. Soc. Jpn.* **2013**, *86*, 230.
[18] D. Cremer, *Isr. J. Chem.* **1980**, *20*, 12.
[19] W. Zou, D. Izotov, D. Cremer, *J. Phys. Chem. A* **2011**, *115*, 8731.
[20] J. P. Schermann, *Spectroscopy and Modelling of Biomolecular Building Blocks*, Elsevier: Amsterdam, **2008**.
[21] a) J. U. Grabow, *Fourier Transform Microwave Spectroscopy Measurement and Instrumentation in Handbook of High Resolution Spectroscopy* (Ed.: M. Quack, F. Merkt), Wiley: Chichester, **2010**, vol. II, pp. 723 – 800; b) W. Caminati, *Microwave Spectroscopy of Large Molecules and Molecular Complexes in Handbook of High Resolution Spectroscopy*, Wiley: Chichester, **2010**, vol. II, pp. 829 – 852.
[22] S. T. Shipman, B. H. Pate, *New Techniques in Microwave Spectroscopy, in Handbook of High Resolution Spectroscopy, Vol. II* (Ed.: M. Quack, F. Merkt), Wiley, Chichester **2010**, pp. 801 – 828.
[23] M. K. Jahn, D. Wachsmuth, D. A. Dewald, J.-U. Grabow, S. C. Mehrotra, *J. Mol. Spectrosc.* **2012**, *280*, 54.
[24] a) C. Pérez, M. T. Muckle, D. P. Zaleski, N. A. Seifert, B. Temelson, G. C. Shields, Z. Kisiel, B. H. Pate, *Science* **2012**, *336*, 897 – 901; b) N. A. Seifert, A. L. Steber, J. L. Neill, C. Pérez, D. P. Zaleski, B. H. Pate, A. Lesarri, *Phys. Chem. Chem. Phys.* **2013**, *15*, 11468 – 11477.
[25] N. L. Allinger, *Pure Appl. Chem.* **1982**, *54*, 2515 – 2522.
[26] V. N. Emel'yanenko, S. P. Verevkin, E. N. Stepurko, G. N. Roganov, M. K. Georgieva, *Russ. J. Phys. Chem. A* **2010**, *84*, 356.
[27] a) U. Andresen, J.-U. Grabow, W. Stahl, *Rev. Sci. Instrum.* **1990**, *61*, 3694; b) J.-U. Grabow, E. S. Palmer, M. C. McCarthy, P. Thaddeus, *Rev. Sci. Instrum.* **2005**, *76*, 093106; c) J.-U. Grabow, W. Stahl, *Z. Naturforsch. A* **1990**, *45*, 1043.
[28] C. D. Cogley, *J. Phys. Chem.* **1987**, *91*, 4235 – 4237.
[29] A. A. Yartseva, L. Sh. Koldrov, S. S. Galibeer, V. P. Arkhireev, N. I. Naumkina, I. A. Litvinov, A. T. Gubaidullin, *J. Struct. Chem.* **2007**, *48*, 1138.
[30] J. K. G. Watson, in *Vibrational Spectra and Structure* (Ed.: J. R. Durig), Elsevier, Amsterdam, **1977**, pp. 1 – 89.
[31] a) J. Kraitchman, *Am. J. Phys.* **1953**, *21*, 17; b) C. C. Costain, *Trans. Am. Crystallogr. Assoc.* **1966**, *2*, 157.
[32] H. D. Rudolph, J. Demaison, in *Equilibrium Molecular Structures: From Spectroscopy to Quantum Chemistry* (Ed. J. Demaison, J. E. Boggs, A. G. Császár), CRC, Boca Raton, **2010**, Chapter 5, pp. 125 – 158.

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