yield, and the sensitive β-hydroxy ketones **14** and **15** are produced in 49% yield with 5:1 selectivity for the equatorial alcohol.

Yields are lower when either the alkene or β-keto ester of the adduct reacts further. The terminal double bonds of **16**, **17**, **20**, and **22** are more susceptible to further attack by electrophiles or electrophilic radicals, which reduces the yield. The β-keto ester moiety of cyclopentanones **17–21** oxidizes more readily than that of cyclohexanones **13–16** at a rate competitive to that of the starting acyclic β-keto ester.[20] The dienone **19** is a product of this overoxidation. Similar products are probably formed from **17** and **20** but undergo polymerization. Oxidative free-radical cyclization of **12** (47%) proceeds in much higher yield than that of **11** (18%), since overoxidation of the β-keto ester is blocked by the methyl group.

These results establish that oxidative free-radical cyclization using $Mn(OAc)_3$ is a valuable method for initiating polyolefin cyclization and is a useful approach for the formation of six- and five-membered carbocycles. Further studies of these reactions are in progress.

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Registry No. **1**, 97690-35-2; **2**, 97690-36-3; **3**, 41437-69-8; **4**, 97690-37-4; **5**, 97690-38-5; **6**, 97690-39-6; **7**, 97690-40-9; **8**, 78249-27-1; **9**, 62344-14-3; **10**, 22617-64-7; **11**, 53067-23-5; **12**, 97690-41-0; **13**, 97690-42-1; **14**, 97690-43-2; **15**, 97690-44-3; **16**, 97690-45-4; **17** (isomer 1), 83221-16-3; **17** (isomer 2), 97690-46-5; **18** (isomer 1), 97690-47-6; **18** (isomer 2), 97747-18-7; **19**, 97690-48-7; **20** (isomer 1), 97690-49-8; **20** (isomer 2), 85642-71-3; **21** (isomer 1), 97690-50-1; **21** (isomer 2), 97690-51-2; **22** (isomer 1), 97690-52-3; **22** (isomer 2), 97690-53-4; **23** (isomer 1), 97690-54-5; **23** (isomer 2), 97690-55-6; $Mn(OAc)_3$, 993-02-2; (±)-podocaspic acid, 15292-90-7.

(20) The relative reactivity of the β-keto esters may correspond to the percent of the keto form present a equilibrium. Acetoacetate and 2-cyclopentanone carboxylate esters are largely ketonic. 2-Oxocyclohexanecarboxylate esters are largely enolic. See: Rhoads, S. J. *J. Org. Chem.* **1966**, *31*, 171. Kol'tsov, A. I.; Kheifets, G. M. *Russ. Chem. Rev. (Engl. Transl.)* **1971**, *40*, 773.

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Relationship of Aromatic Nitro Group Torsion Angles with ^{17}O Chemical Shift Data

Summary: The ^{17}O chemical shifts of seven aromatic nitro groups have been shown, for the first time, to vary with the torsion angle that describes the orientation of the nitro group with respect to the atoms of the aromatic ring. A quantitative relationship between ^{17}O chemical shift data and the torsion angle is reported.

Sir: ^{17}O nuclear magnetic resonance spectroscopy is becoming an increasingly important method in organic chemistry.[1] Despite poor receptivity, the large chemical shift range for this nucleus makes it particularly attractive for examining the influences of subtle changes in molecular structure. We report a relationship between the ^{17}O chemical shift data and the average torsional angle that describes the orientation of the nitro group and the aromatic ring as approximated by X-ray diffraction data.

The influence of electronic effects on ^{17}O chemical shifts of meta- and para-substituted nitrobenzenes has recently been well documented.[2] However, despite the fundamental interest in the molecular structure of complex aromatic nitro compounds[3] and the limited understanding of the role played by sterically crowded aromatic nitro groups in compounds that display important biological activity,[4] no systematic effort to correlate molecular structure for these types of compounds with ^{17}O chemical shifts has appeared. In pioneering work with ^{17}O NMR spectroscopy, Christ and Diehl noted that the chemical shift of *o*-nitrotoluene was downfield from *p*-nitrotoluene by approximately 30 ppm.[5] This shift is presumably, in large part, a result of steric inhibition of conjugation of the nitro group with the aromatic ring.

The ^{17}O chemical shifts of a series of sterically crowded aromatic nitro compounds have been determined[6] as 0.5 M solutions in dried acetonitrile at 75 °C (Table I). Included in the table are chemical shift values determined under these conditions for appropriate unhindered nitro

Table I. ^{17}O Chemical Shifts for Aromatic Nitro Compounds

compd	name	chemical shift,[a]
1	nitrobenzene	575
2	1-nitronaphthalene	605
3	9-nitroanthracene	637
4	2-nitronaphthalene	575
5	1,5-dinitronaphthalene	612
6	1,3-dinitronaphthalene	609, 578
7	1,8-dinitronaphthalene	599
8	*o*-nitrotoluene	602
9	*p*-nitrotoluene	572
10	2,4-dimethylnitrobenzene	597
11	2,3-dimethylnitrobenzene	612
12	2,6-dimethylnitrobenzene	629
13	2,4,6-trimethylnitrobenzene	628
14	2,4,6-tri-*tert*-butylnitrobenzene[b]	657
15	*p*-dinitrobenzene	584
16	*m*-dinitrobenzene	579
17	*o*-dinitrobenzene	609

[a] Taken at 75 °C as 0.5 M solution in dried acetonitrile [2-butanone (0.5%), 558 ± 1 ppm, as an internal check]. [b] Measured at 0.3 M solution because of solubility limitations.

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(6) The ^{17}O spectra, natural abundance, on a JEOL GX-270 spectrometer equipped with a 10-mm broad-band probe operated at 36.5 MHz. The NMR spectra were acquired at natural abundance on 0.5 M solutions in dried acetonitrile (distilled over CaH_2 and stored over molecular sieves) at 75 °C. The chemical shift data were referenced to external water (0.5% 2-butanone was added as an internal check, 558 ± 1 ppm). The instrument settings were either 25-kHz spectral width, 2K data points, 90° pulse angle (28 μs pulse width), 0.3 ms acquisition delay, and 41 ms acquisition time or 30.12-kHz spectral width, 0.25 ms acquisition delay, and 34 ms acquisition time. The spectra were recorded with sample spinning and without lock. The signal-to-noise ratio was improved by applying a 50-Hz exponential broadening factor to the FID prior to Fourier transformation. The data point resolution was improved to ±0.2 ppm by zero filling to 8K data points. Generally, spectra with S/N of about 10/1 were obtained after $\sim 10^5$ scans. Under these conditions, the half-height band widths were 230 ± 30 Hz, except for **3**, 330 Hz, and **14**, 380 Hz. The reproducibility of the chemical shifts is estimated to be ±2 ppm. The nitro compounds studied were commercially available.

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aromatic reference compounds. On comparison of the chemical shifts of nitrobenzene (**1**), 1-nitronaphthalene (**2**), and 9-nitroanthracene (**3**), a substantial deshielding trend is noted. Increasing nitro group–aromatic ring orbital overlap with increasing ring size would be expected to result in increasing single bond character of the nitro function and should be reflected by a shielding trend. The opposite is observed with the chemical shift trend **3** > **2** > **1**, corresponding to increasing nitrogen–oxygen double bond character of the respective nitro groups, which can be explained in terms of increasing rotation of the nitro group from the plane of the aromatic ring. The peri interactions in **2** and **3** are expected to cause significant rotation of the nitro groups from the plane of the rings, and the available X-ray data for **1** and **3** support this prediction. The torsion angle that describes the orientation of the nitro group with respect to the atoms of the aromatic ring is reported to be 0° for **1**[7] and 85° for **3**.[8]

In contrast to the chemical shift data for **2**, the value of its isomer 2-nitronaphthalene (**4**), devoid of peri interactions, is 575 ppm, unchanged from that of nitrobenzene. The chemical shift values for the dinitronaphthalenes 1,5-dinitro- (**5**), 1,3-dinitro- (**6**), and 1,8-dinitronaphthalene (**7**) reflect steric influences. The value for **5** is in reasonable accord with that of **2**, taking into account the fact that the two nitro groups in **5** must have some electronic effect upon each other. X-ray data show that the nitro groups of **5** are rotated by 48.7° from the plane of the aromatic ring;[9] the downfield shift of **5** and thus **2** are consistent with increased nitrogen–oxygen double bond character. The two chemical shift values for **6** differ little from the values of the corresponding nitro groups of **2** and **4**. The chemical shift value for **7** is shielded by 6 ppm in comparison to **2**, a somewhat surprising result. However, in the solid state, the nitro groups in **7** are rotated from the plane of the aromatic ring by only 43°.[10] Consequently, if this conformational preference carries over to the solution phase, the relative shifts of **5**, **6**, and **7** can be understood, at least in part, in terms of the magnitude of the torsional angle.

The apparent relationship between torsion angle and ^{17}O chemical shift can be explored further by examining the data for several alkyl substituted nitrobenzenes and dinitrobenzenes (**8**–**17**). Generally, an increasing amount of deshielding with increasing steric hindrance is observed for the ortho-substituted compounds in Table I. Using ^{17}O chemical shift values obtained for a meta-substituted methyl group[2c] (−0.4 ppm) and assuming the electronic contribution for ortho- and para-substituted methyl groups are equivalent, we estimate that the deshielding values due to steric inhibition of resonance for 2,4-dimethylnitrobenzene (**10**), 2,3-dimethylnitrobenzene (**11**), 2,6-dimethylnitrobenzene (**12**), and 2,4,6-trimethylnitrobenzene (**13**) to be 35, 47, 67, and 66 ppm, respectively. These shifts reflect increasing nitrogen–oxygen double bond character, which would be expected as the nitro group is rotated from the plane of the aromatic ring. A similar trend for the ^{15}N chemical shift of the nitro group was noted for **11** and **12**; however, the magnitude of the shifts was substantially smaller.[11] For example, making the same assumptions for ^{15}N shifts concerning the electronic contributions of methyl

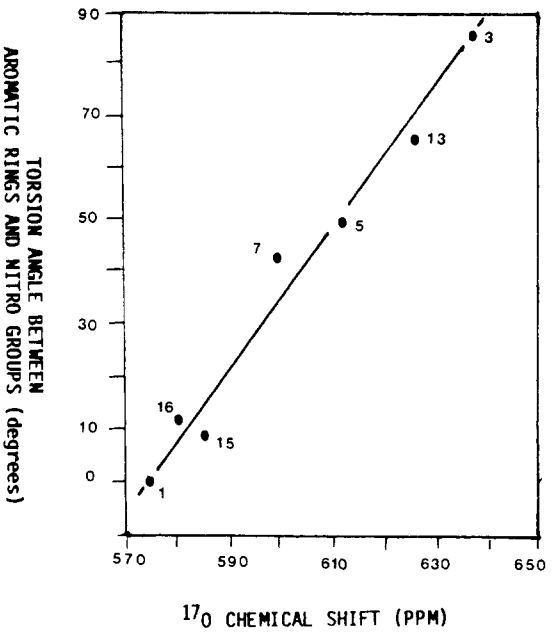

Figure 1. Plot of torsional angle between aromatic rings and nitro groups vs. the ^{17}O chemical shifts (ppm) data.

groups as mentioned above for the ^{17}O shifts, it is noted that the ^{15}N signal of **12** is deshielded by only 9 ppm,[11] a factor of 7 less than the effect on the ^{17}O shifts. We have recently noted that the ^{17}O chemical shift data of a series of pyridine *N*-oxides were more sensitive to structural changes than the ^{15}N chemical shifts.[12]

Interestingly, 2,4,6-tri-*tert*-butylnitrobenzene (**14**) exhibits a substantial downfield shift, showing a chemical shift value of 657 ppm. It is reasonable to assume that the electronic effects of the alkyl substituents for **13** and **14** are comparable; hence, the substantially greater downfield shift for **14** can be attributed to several factors. These could include increased average torsion angle of the nitro group from the plane of the aromatic ring for **14**, additional compressional effects arising from direct interaction of the *tert*-butyl groups with the nitro group oxygen atoms, and distortion of the benzene ring planarity as a result of extensive steric crowding.

The data for the several nitro aromatic compounds discussed above suggested a quantitative relationship between the ^{17}O chemical shift of the nitro function and the torsional angle between the aromatic ring and their nitro groups. Using X-ray data previously reported for **1**,[7] **3**,[8] **5**,[9] **7**,[10] **13**,[13] **15**,[14] and **16**,[15] we have plotted the value for the torsional angle between the nitro group and the aromatic ring vs. the ^{17}O chemical shifts. Figure 1 shows a good correlation between torsional angle and ^{17}O chemical shift for seven nitro aromatic compounds. The relationship is torsional angle = $(1.29 \pm 0.24)\delta - 739$; $r = 0.986$, 95% confidence limits for error in slope. Apparently the torsional angle observed in the solid state is a surprisingly good estimate of the average solution phase angle. In cases where electronic effects are small, this relationship allows one to estimate average torsional angles for aromatic nitro compounds from ^{17}O chemical shift data. Such a relationship should be general for other functional groups, for example, carbonyl groups. We are presently exploring such systems.

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Registry No. 1, 98-95-3; 2, 86-57-7; 3, 602-60-8; 4, 581-89-5; 5, 605-71-0; 6, 606-37-1; 7, 602-38-0; 8, 88-72-2; 9, 99-99-0; 10, 89-87-2; 11, 83-41-0; 12, 81-20-9; 13, 603-71-4; 14, 4074-25-3; 15, 100-25-4; 16, 100-25-4; 16, 99-65-0; 17, 528-29-0.

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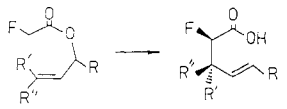
Facile Diastereoselective Ester Enolate Claisen Rearrangements of Allyl Fluoroacetates

Summary: The diastereoselective ester enolate Claisen rearrangement of allyl fluoroacetate esters results from stereoselective deprotonation of the ester to form the *E* enolate.

Sir: The power and the utility of the Claisen rearrangement has led to its popular use in synthesis.[1] The Ireland ester enolate Claisen rearrangement has extended the applicability of the rearrangement by facilitating its employment in convergent approaches.[2] It is well established that the reaction is tolerant of α substitution.[3] The effect of fluorination on sigmatropic rearrangement has been reported in only a few cases, and the effect of fluorination on the Claisen rearrangement in particular has not previously been described. We were therefore pleased to find that allyl fluoroacetates undergo a facile and diastereoselective ester enolate Claisen rearrangement which may have general synthetic utility.



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In our studies of the synthetic utility of the ester enolates of fluoroacetic acid, we were frustrated by the poor diastereoselectivity of these reagents in directed aldol reactions.[4] In the Claisen rearrangement, we observed that excellent diastereoselectivity was possible, as high as 20:1, as determined by both ^{13}C and ^{19}F NMR, in good overall yield. This diastereoselectivity requires the stereoselective deprotonation of the ester to form only one enolate. Control experiments where the rearrangement was conducted with excess base demonstrated that the product trimethylsilyl esters are readily epimerized to a thermodynamic mixture. Previously generation of the enolate of ethyl fluoroacetate with excess lithium hexamethyldisilazide (LHMDS) followed by trapping experiments with chlorotrimethylsilane indicated that both the *E* and *Z* enolates were being formed.[4a]

The best diastereoselectivity and yields were obtained when lithium diisopropylamide (LDA) was used to generate the enolate.[5] When formation of the enolate of allyl fluoroacetates with LHMDS under comparable conditions was attempted, the yields of rearranged products were consistently low. Excess LDA masked the diastereoselectivity of the rearrangement by epimerizing the products. The well-documented effect of hexamethylphosphoramide (HMPA) on the enolate geometry,[6] promotion of the formation of *Z* enolates,[7] was not observed. The addition of HMPA did degrade the diastereoselectivity of the rearrangement slightly (See Table I).

The facile rearrangement of fluorinated substrates predicted by a number of different criteria was confirmed by these experiments. The thermodynamic analysis of the Cope rearrangement of 1,1-difluoro-1,5-hexadiene to 3,3-difluoro-1,5-hexadiene suggests the energy of activation is lowered 2.5 kcal/mol relative to the unfluorinated diene,[8] with the result of the equilibrium being shifted to favor formation of 3,3-difluoro-1,5-hexadiene exclusively. Quantitative observations of NMR spectra of monofluorobullvalene, which undergoes Cope rearrangements,[9] suggest the equilibria have also been displaced by fluorination.

Carpenter's resonance energy model, based upon the calculated difference in Hückel π-electron energy for suitable reactant and transition-state models, predicts π donors would lower the difference in reaction enthalpy.[10] Fluorine, a π donor, would therefore result in an increase in resonance energy in preceding from the reactant to the transition-state model, and the rearrangement would be accelerated.

Comparison of the half-lives of fluoroacetate allyl esters with published half-lives and rate constants from the literature demonstrate there is a slight but definite acceleration of the rearrangement upon fluorination. The

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(5) Typical procedure: To a magnetically stirred, three-necked round-bottomed flask containing 20 mL of anhydrous THF and 0.0044 mol of lithium diisopropylamide (prepared in the usual manner at 0 °C), under an inert atomosphere at −100 °C, was added dropwise over 2 min 0.0037 mol of an allyl fluoroacetate dissolved in 5 mL of THF. After 3 min, 0.0044 mol of chlorotrimethylsilane was rapidly added. The mixture was allowed to warm to 0 °C and then was stirred at 40 °C for 2–4 h. The reaction mixture was quenched with methanol and was exhaustively extracted with 5% sodium hydroxide. The combined basic extract was washed twice with 10 mL of ether and then was acidified with concentrated HCl. The product acids were extracted with dichloromethane, were washed with brine, and were dried over anhydrous magnesium sulfate. The crude product was isolated by rotary evaporation of the solvent.

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