the usual procedures of drying solvents and cells cannot prevent the presence of water in the solutions at concentrations at least as high as those of the compounds and the amines, i.e., 10^{-3}–10^{-5} M. In the absence of experiments under "superdry" conditions it is not possible to assess the effect of such water traces. However, the very pronounced effect of amines on the kinetics observed in solutions containing such water traces remains an experimental fact. In nonpolar solvents it is reasonable that the compounds studied, as well as the amines, form associates with these traces of water.

Registry No.—Ia, 1522-20-9; Ib, 1704-14-9; Ic, 65311-55-9; Id, 65311-56-0; Ie, 1704-15-0; Ig, 1522-33-4; Ih, 65311-57-1; IIa, 123-54-6; IIb, 93-91-4; IIc, 13298-50-5; IId, 50593-99-2; IIe, 120-46-7.

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Photochemistry of Epoxides. 4. Photoreduction of a Monoepoxide of *endo*-Dicyclopentadiene[1a]

Donald R. Paulson,* A. Spencer Murray,[1b] and Eric J. Fornoret[1c]

Department of Chemistry, California State University, Los Angeles, Los Angeles, California 90032

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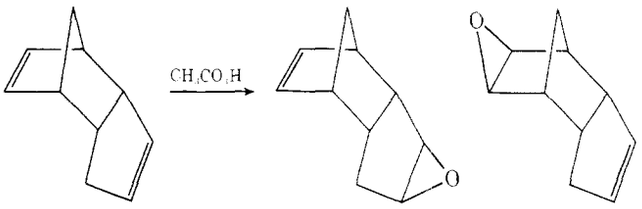
Two monoepoxides of *endo*-dicyclopentadiene have been prepared by peracetic acid oxidation. Acetone sensitized photolysis of *endo*-4-oxatetracyclo[6.2.1.$0^{2,7}$.$0^{3,5}$]undec-9-ene (**1**) results in efficient photoreduction of the double bond via a free-radical mechanism. Photolysis of model compounds indicates that there is no interaction between the triplet state excited olefin and the epoxy moiety.

Photochemical $2\pi + 2\pi$ intramolecular cyclizations have been used extensively in the synthesis of polycyclic molecules.[2] Recently, $2\pi + 2\sigma$ photochemical cyclizations have been reported by Prinzbach and others.[3] As a continuation of our studies into the photochemical interaction of olefinic and epoxide moieties,[4] we have investigated the acetone sensitized photolysis of the monoepoxides of dicyclopentadiene. These molecules were chosen for study because the close proximity of the olefinic π bond and the carbon–carbon σ bond of the epoxy group might make them amenable to $2\pi + 2\sigma$ intramolecular photocyclization.

Peracetic acid epoxidation of *endo*-dicyclopentadiene gave two monoepoxides in a 1:1.5 ratio. The major product is assigned as *endo*-9-oxatetracyclo[5.3.1.$0^{2,6}$.$0^{8,10}$]undec-3-ene (**2**) while the minor product is assigned as *endo*-4-oxatetracyclo[6.2.1.$0^{2,7}$,$0^{3,5}$]undec-9-ene (**1**). The structures of these two epoxides were first correctly assigned by Alder and Stein.[5] However, they did not obtain a pure sample of epoxide **1**. The assigned structures are readily confirmed by infrared and NMR analysis. Epoxide **1** shows strong absorption at 835 cm^{-1} which is characteristic of the epoxycyclopentane system[6] while epoxide **2** shows strong absorption at 850 cm^{-1} which is characteristic of the 2,3-epoxybicyclo[2.2.1]heptane system.[6] The NMR spectrum of epoxide **2** has an AB pattern centered at δ 1.1 for the protons at C_{11}. This clearly indicates an *exo*-nornornyl epoxy group.[7] The remainder of the spectral data is consistent with the assigned structures (see Experimental Section).

The photochemistry of **1** and **2** was then investigated. Epoxide **2** was found to be essentially inert in both polar and nonpolar solvents using a wide variety of sensitizers and exciting wavelengths. In marked contrast, however, photolysis of **1** in degassed acetone solutions with a 450 W Hanovia medium pressure lamp equipped with a Pyrex filter resulted in formation of **3**[6] in 18–36% yield, **4** (and **4'**) in 14–33% yield, and 2,5-hexandione in 2–10% yield. Low concentrations of **1** (0.01 M) favored **3** while higher concentrations of **1** (0.5 M) favored **4** (**4'**).



1 **2**

The infrared spectrum of **3** has a strong band at 838 cm^{-1} as expected for an epoxycyclopentane system. We were unable to completely separate **4** and **4'**. However, the infrared spectrum displays a carbonyl band at 1710 cm^{-1} and a strong epoxy cyclopentane band at 837 cm^{-1}. The NMR shows the methyl ketone at δ 2.10.

In order to determine the effect, if any, of the epoxide functional group upon the photoreactivity of **1** and **2**, the photolysis of **5**[6] and **6**[8] was investigated.

In analogy to epoxide **2**, compound **5** was found to be essentially inert to a wide variety of photochemical conditions. However, photolysis of **6** in acetone solution resulted in the formation of **7**[9] (14–28%), **8** (30–48%), and 2,5-hexandione

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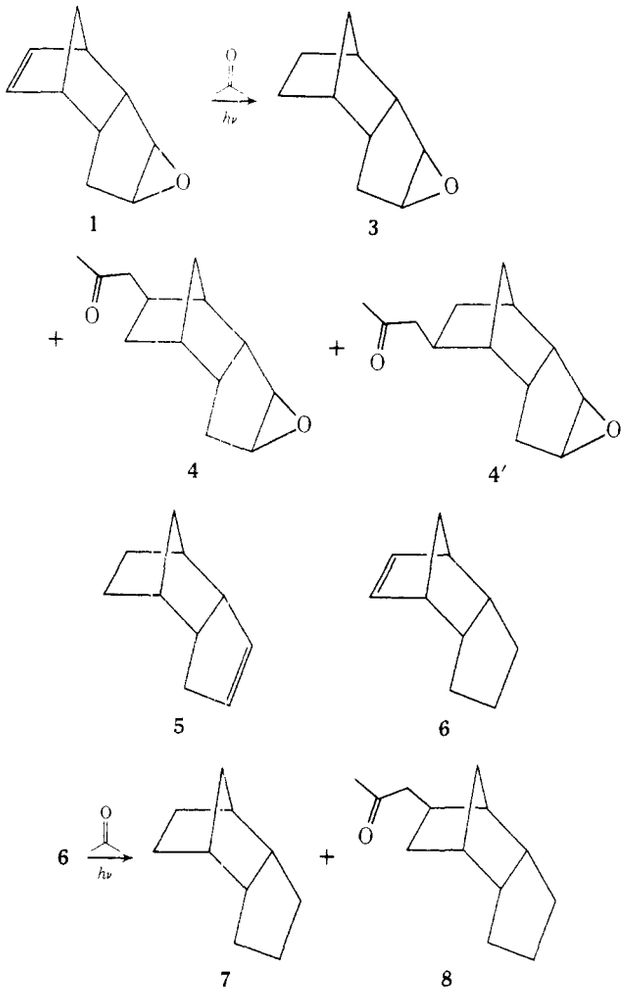
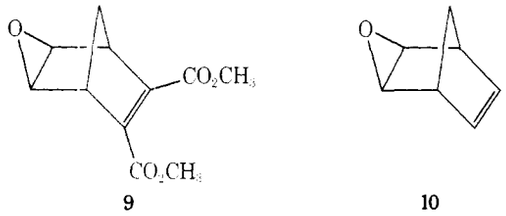


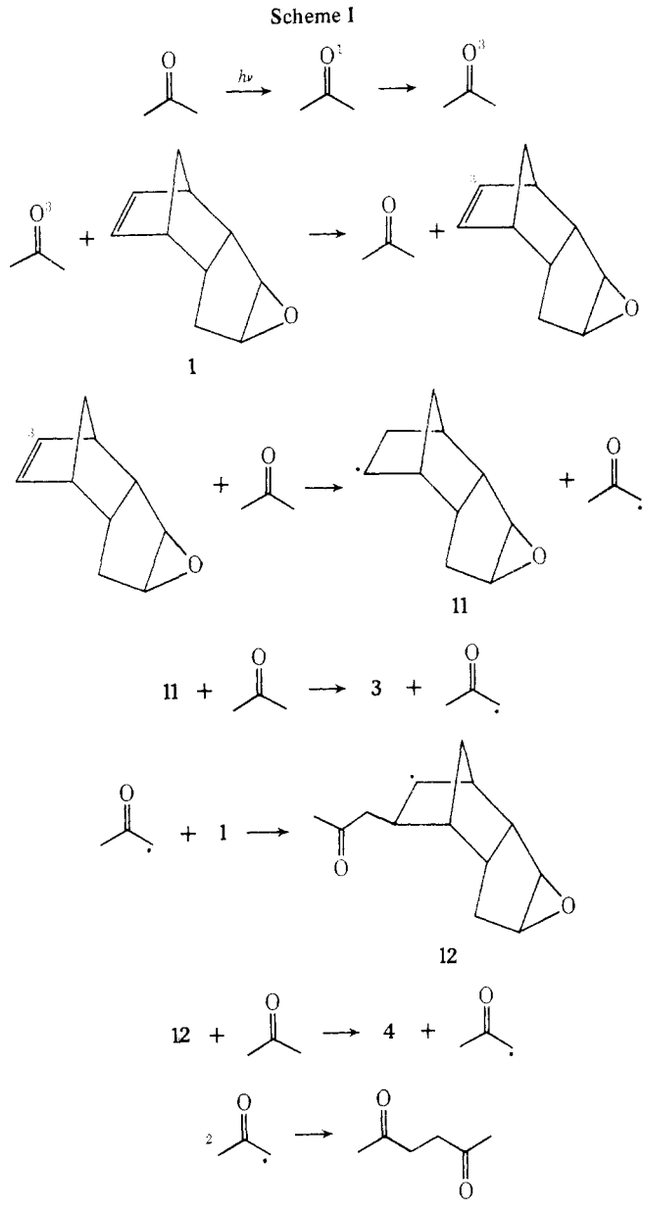
(1–2%). Again, low concentrations of **6** favored formation of the photoreduced compound **7** while higher concentrations of **6** favored the acetonyl addition compound **8**. Thus the photochemistry of this system is unaltered by the presence of the epoxide functionality.

In contrast to our results, compound **9** undergoes competitive $2\pi + 2\sigma$ cyclization and photoreduction[3] while in our system only photoreduction was observed. The difference in reactivity between **1** and **9** is probably due to an excited state of much lower energy in **9**, due to the extended conjugation. Thus the hydrogen abstracting ability of the triplet excited state of **9** would be greatly diminished over that of **1** and cyclization can now effectively compete with hydrogen abstraction. In accord with this explanation, photolysis of **10** in acetone yielded only the photoreduction product.[10]



Mechanistically the reaction probably proceeds through a photosensitized free-radical chain process. The mechanism is shown below; however, other possible sensitized mechanisms could also be postulated. The reaction is initiated by energy transfer from triplet state acetone to yield triplet state **1**. Hydrogen abstraction from acetone by triplet state **1** produces **11** and an acetonyl radical. A second hydrogen abstraction produces **3** and another acetonyl radical. The 2,5-

Scheme I



hexandione arises via radical coupling of two acetonyl radicals. A radical coupling between **11** and an acetonyl radical could account for the formation of **4** (**4′**); however, it is not reasonable for the major product in a free-radical transfer process to occur via a termination step. A more plausible pathway would be the addition of acetonyl radicals to the double bond to produce **12** followed by another abstraction from acetone giving **4**. The exo face is usually the preferred position of attack on norbornene systems by free radicals.[1]

Similar photoreactions to those described here have been reported. Sauers has observed both acetonyl radical addition and photoreduction of several norbornenes by photolysis in acetone.[12] Srinivasin and Hill report[13] an acetonyl addition to cyclobutene under similar conditions. Using considerably higher concentrations than used in the present study, Sharf[14] has observed acetonyl addition and dimerization of tetracyclic homologues of norbornene during photolysis in acetone. These reactions presumably proceed by the same mechanism as those in the present study. The balance between photoreduction, acetonyl addition, and dimerization appears to be a delicate function of the olefin concentration. At very high concentrations (5–10 M) acetone sensitization results in mainly dimerization while at moderate concentrations (~1 M) acetonyl addition products predominate. Finally, at very

low concentrations of olefins, the simple photoreduction becomes a major process.

The possibility still existed that the $2\pi + 2\sigma$ cycloaddition of **1** was a viable reaction but one that proceeded an order of magnitude slower than the abstraction of hydrogen from the acetone sensitizer. In view of the known resistance of cyclopropyl groups to hydrogen abstraction,[15] it was felt that dicyclopropyl ketone (DCK) might be an ideal sensitizer to effect the desired cycloaddition. However, irradiation of **1** in the presence of DCK did not result in any photoreaction of **1**. This lack of photoreactivity could be due to a triplet energy of DCK that is too low to efficiently generate norbornene triplets.

Photolysis of dicyclopentadiene (1%) in the presence of DCK produced the expected intramolecular cycloaddition product[16] in excellent yield. Photolysis of norbornene in 10% DCK/benzene yielded the norbornene dimers in a 1:8 ratio in agreement with that reported for acetone sensitization.[17] Furthermore, there was no photoreduction of the norbornene as occurs in the case of acetone sensitization.

These results indicate that DCK is an excellent triplet sensitizer for norbornene type molecules since it does not produce concurrent photoreduction of the alkene. Finally, these results show that intramolecular $2\pi + 2\sigma$ photocyclization will not occur from the triplet state of **1** even when the photoreduction route is completely suppressed.

Experimental Section

Infrared spectra were obtained with a Perkin-Elmer Model 137 spectrophotometer. Nuclear magnetic resonance spectra were obtained with a Varian A-60 spectrometer. Melting points were taken in a Hoover-Thomas Capillary Melting Point Apparatus and are uncorrected. Gas chromatography (GPC) was performed on F & M Model 700 and Model 701 gas chromatograph. The analytical column was 10 ft × ⅛ in. 15% carbowax 20 M on 60–80 Chromosorb W; the preparative column was 10 ft × ⅜ in. 15% carbowax 20 M on 60–80 Chromosorb W. Percentage composition data were estimated by peak areas. Microanalyses were performed by Chemalytics, Inc., Tempe, Ariz.

Epoxidation of Dicyclopentadiene. To an ice-cold mechanically stirred mixture of 15.0 g (0.133 M) of *endo*-dicyclopentadiene and 105 g of anhydrous sodium carbonate in 225 mL of methylene chloride was added dropwise 24.9 g (0.131 M) of 40% peracetic acid which had been pretreated with a small amount of sodium acetate. After addition was complete the mixture was stirred at room temperature until the solution gave a negative starch–iodide test (~20 h). The solid salts were removed by suction filtration and washed well with an additional 250 mL of solvent. The solvent was removed from the filtrate by flask evaporation to give 20 g of crude product. GLC analysis of the crude product showed unreacted dicyclopentadiene and two products in the ratio of 1:1:1.5. Column chromatography of 4.0 g of crude product over silica gel using benzene as eluent gave 1.0 g of pure **1** and 1.2 g of pure **2**. The minor product **1** was identified as *endo*-4-oxatetracyclo[6.2.1.$0^{2,7}$.$0^{3,5}$]undec-9-ene, mp 85–86 °C. The infrared spectrum (CCl_4) of **1** displays strong bands at 725 and 835 cm^{-1} and weak absorption at 1625 cm^{-1}. The NMR spectrum shows (CCl_4) 4-proton multiplet at δ 1.1–2.1, 6-proton multiplet at 2.3–3.3, and a 2-proton multiplet (CH=CH) centered at 6.04. Anal. Calcd for $C_{10}H_{12}O$: C, 81.04; H, 8.16. Found: C, 81.36; H, 8.26.

The major product was identified as *endo*-9-oxatetracyclo[5.3.1.$0^{2,6}$.$0^{8,10}$]undec-3-ene (**2**),[5] mp 76–78 °C (lit.[5] mp 79–80 °C). The infrared spectrum (CCl_4) shows absorption at 1640 (weak), 850, and 706 cm^{-1}. The NMR (CCl_4) shows an AB pattern (J = 9.0 Hz) centered at δ 1.098, a 10-proton multiplet from 2.1–3.3, and a 2-proton broad singlet at 5.6.

Photolysis of 1. A. Preparative. A 1.0-g sample of epoxide **1** was dissolved in 100 mL of spectral grade acetone, degassed for 10 min by bubbling nitrogen through the solution and photolyzed for 100 min with a Hanovia 450 W medium pressure lamp equipped with a Pyrex filter. The acetone was removed by flash evaporation to give a gummy mass which was extracted with petroleum ether. The petroleum ether was removed by flash evaporation to give 0.54 g of greenish yellow oil. GPC analysis showed three volatile products in the ratio of 6:1:3.8. The three products were separated by preparative GPC.

The major product was identified as *endo*-4-oxatetracyclo[6.2.1.$0^{2,7}$.$0^{3,5}$]undecane (**3**) by direct comparison with an authentic sample.[6]

Table I

[1], M	% 3	% 2,4-hexandione	% 4 (4′)
0.017	36	11	14
0.034	34	6	
0.068	30	5	19
0.136	23	2	
0.204	18	2	33

Table II

[6], M	% 7	% 8
0.018	28	36
0.068	22	48
0.340	14	45

The second product was identified as 2,4-hexandione by direct comparison with an authentic sample.

The third product is assigned as a mixture of the two *exo*-acetonyl compounds **4** and **4′**. They could not be separated by GPC or column chromatography. The sample shows IR (CCl_4) band at 1725 (C=O) and 838 cm^{-1} (epoxide). The NMR spectrum (CCl_4) showed a 3-proton singlet at δ 1.90 ($\mathbf{CH_3}$C=O). They are assigned the *exo*-acetonyl stereochemistry based on analogy to free-radical additions to norbornene systems.[11]

Photolysis of 0.5 g of **1** in 50 mL of degassed DCK or 50 mL of 10% DCK/benzene with a 450 W medium pressure Hanovia lamp equipped with a Pyrex filter resulted in no detectable volatile products.

B. Chemical Yield Studies. Samples of varying concentration were photolyzed in degassed acetone solutions using a merry-go-round apparatus and either Rayonet RPR-3000 Å bulk in Pyrex tubes or Rayonet RPR -2537 Å bulbs in quartz tubes. The overall results were essentially the same. Table I lists the maximum yields (calculated using eicosane as internal standard) which were obtained of the three photoproducts at 2537 Å.

Photolysis of Bicyclo[5.2.1.$0^{2,6}$]dec-8-ene (6). A 1.0-g sample of **6**[8] was dissolved in 100 mL of spectral grade acetone, degassed for 10 min by bubbling nitrogen through the solution, and photolyzed for 90 min with a Hanovia 450 W medium pressure lamp equipped with a Pyrex filter. Nitrogen was bubbled through the solution throughout the irradiation. The acetone was removed by rotary evaporation to give a yellow oil. GPC analysis showed two photoproducts and unreacted **6** in the ratio of 1:2:1. The products were isolated by column chromatography over silica gel using benzene as eluent. A trace of 2,4-hexanedione was also isolated. The minor product was identified as bicyclo[5.2.1.$0^{2,6}$]decane (**7**) by comparison with an authentic sample.

The major product was assigned as *exo*-8-acetonyltricyclo[5.2.1.$0^{2,6}$]decane (**8**). The exo stereochemistry is assigned base on analogy to other norbornyl systems.[11] Compound **8** has a strong infrared band at 1710 cm^{-1} (C=O). The NMR spectrum shows two distinct features of interest: a three-proton singlet at δ 2.01 and a broad two-proton doublet at δ 2.23 (J = 2.0 Hz) indicating an acetonyl group attached to a tertiary carbon. Anal. Calcd for $C_{13}H_{20}O$: C, 81.20; H, 10.48. Found: C, 80.90; H, 10.55.

B. Chemical Yield Studies. Samples of varying concentrations were photolyzed in degassed acetone solutions using a merry-go-round apparatus and Rayonet RPR-3000 Å lamps. Table II lists the maximum yields (calculated using *n*-dodecane as internal standard) which were obtained of the two photoproducts.

Photolysis of Dicyclopentadiene. A 20-μL sample of dicyclopentadiene in 2 mL of DCK was degassed by bubbling nitrogen for 3 min and then irradiated at 3000 Å in a Pyrex tube. The only observed product was the intramolecular $2\pi + 2\pi$ cycloaddition product, identified by comparison with an authentic sample.[16]

Photolysis of Norbornene. A solution of 0.5 g of norbornene, 1.5 mL of benzene, and 100 μL of DCK was degassed by bubbling nitrogen for 3 min and irradiated in a Pyrex tube at 3000 Å. The reaction was followed by GPC. The only observable products were the two norbornene dimers (8:1 ratio).[17]

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Nuclear Magnetic Resonance Spectroscopy. Carbon-13 and Nitrogen-15 Spectra of the Penicillins and Cephalosporins

Jonathan W. Paschal and Douglas E. Dorman*

The Lilly Research Laboratories, Indianapolis, Indiana 46206

Puliyer R. Srinivasan and Robert L. Lichter

Department of Chemistry, Hunter College of the City University of New York, New York, New York 10021

Received September 1, 1977

^{13}C and ^{15}N NMR spectra of a selection of penicillin and cephalosporin antibiotics are reported and evaluated. The ^{13}C data seem in broad accord with the present theory of ^{13}C chemical shifts. ^{15}N chemical shifts are complicated by solvent effects, and correlations with structure are frequently difficult to recognize. While ^{15}N chemical shifts show no obvious relationship to biological activity, some correlations are possible in the case of ^{13}C.

The contributions of nuclear magnetic resonance (NMR) spectroscopy to studies of the structure and conformations of penicillins and cephalosporins have been many and varied.[1] Because of the relative simplicity of these molecules, routine ^1H NMR spectra usually suffice to elucidate their structures. Nuclear Overhauser enhancement (NOE) measurements provide further information regarding configuration and conformations in these systems.[1] In the rare cases wherein ^1H NMR spectroscopy fails to distinguish structural possibilities, the ^{13}C NMR spectra can be used.[2] As part of a general exploration of the applicability of ^{15}N NMR spectroscopy to organic and biological chemistry, we have measured the ^{15}N NMR spectra of a number of penicillin and cephalosporin derivatives.[3] The purpose of the present paper is to report these results and to provide additional data regarding ^{13}C chemical shifts in these systems.

Experimental Section

Spectra were measured at natural abundance on JEOL PFT-100 multinuclear spectrometers, using the SD-HC heteronuclear decoupler. Data were collected into the JEOL EC-100 computer. Operating frequencies were 10.09 MHz for ^{15}N and 25.03 MHz for ^{13}C spectra. ^{15}N spectra were accumulated over a 4-KHz sweep width in 8 K of memory, using 15–25° tip angles and 1.2–2.0 s repetition rates. Depending on sample, accumulation times ranging from 6 to 16 h were required to obtain satisfactory signal-to-noise ratios. Data were collected and transformed under conditions which would be expected to lead to 0.7–2.0 Hz line broadening.

Whenever possible, spectra were measured in neutral or near-neutral aqueous solutions. Enough D_2O (10%) was added to provide internal lock. Carbon chemical shifts were measured relative to internal 1,4-dioxane and adjusted to the Me_4Si scale by the relation: $\delta_C(Me_4Si) = \delta_C(\text{diox}) + 67.4$. ^{15}N chemical shifts were measured relative to external NH_4Cl (2.9 M) dissolved in 1 M HCl.

^{13}C and ^{15}N resonance assignments are based on chemical shifts,[4] off-resonance and single-frequency decoupling experiments,[4] relative peak heights,[3] and partial exchange experiments.[5]

Results and Discussion

Penicillins. The structures of the penicillins studied in this work appear in Figure 1. ^{15}N chemical shift data for both the free antibiotics and their methyl esters are presented in Table I. Inasmuch as the ^{15}N spectra of the free antibiotics were measured in aqueous solutions at pH ~6, the carboxylic acid may be assumed to be fully deprotonated.

For the free penicillins, the lactam resonance appears at about 144 ppm. In penicillin V α-sulfoxide, the N(4) resonance is substantially shielded (125.9 ppm), as might be expected from the usual γ effect of oxygen in ^{15}N chemical shifts.[6,7] Because the rigid penicillin nucleus prevents the oxygen from approaching N(4) closely, this shielding cannot be due to a steric effect. This is in agreement with other studies[4b] which show that steric interactions are not essential to the shielding effects of γ heteroatoms.

Except for the example of hetacillin, the lactam nitrogen chemical shifts in these penicillins appear to be relatively insensitive to changing substitution at N(6'). The case of hetacillin is unique in that N(6') is incorporated into a lactam ring which bears bulky substituents. In those β lactams which have been studied by x-ray crystallography,[8] the amide N–H has been shown to be projected above the β-lactam ring. In an

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