119. Photooxygenolytic Degradation of the Vitamin-B_{12} Derivative Heptamethyl *Coα,Coβ*-Dicyanocobyrinate. Efficient Preparation of Bicyclic Fragments

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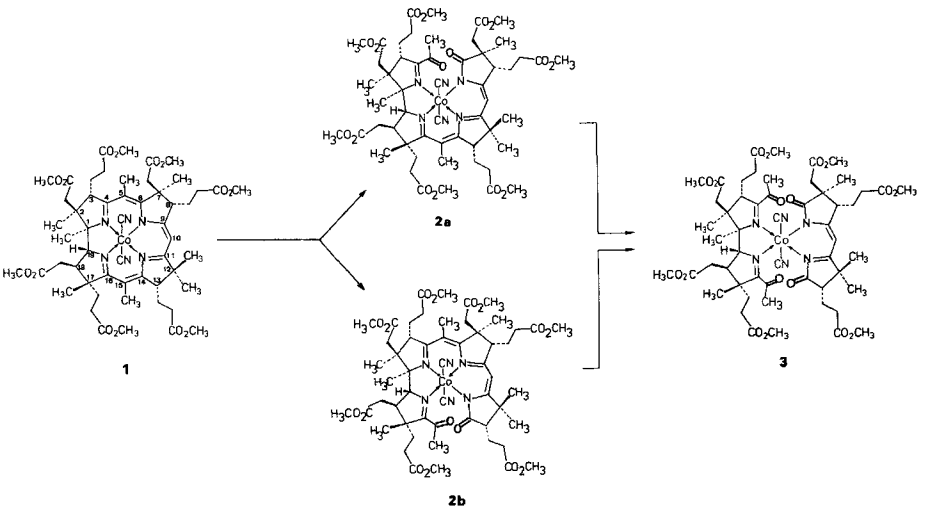
The methylene-blue sensitized photooxygenation of heptamethyl *Coα,Coβ*-dicyanocobyrinate (**1**, cobester) at *ca.* –45° and in (D_3)acetonitrile solution proceeds readily to the stage of selective double cleavage of the corrin macrocycle. It furnishes the bisected heptamethyl *Coα,Coβ*-dicyano-5,6:14,15-tetraoxo-5,6:14,15-disecocobyrinate (**3**) in 91% yield after warming the photooxygenation mixture to room temperature. Complex **3** is also obtained by photooxygenation of the secocorrinoid oxygenation products of **1**, namely of heptamethyl *Coα,Coβ*-dicyano-5,6-dioxo-5,6-secocobyrinate (**2a**) and of its isomer heptamethyl *Coα,Coβ*-dicyano-14,15-dioxo-14,15-secocobyrinate (**2b**). When the raw photooxygenation product of **1** is kept at low temperature, **3** is not formed in a significant amount; spectral analysis reveals **4** as intermediate that is transformed into **3** quantitatively upon warm-up and storage at r.t. Compound **4** is assigned the structure of heptamethyl *Coα,Coβ*-dicyano-5,6-epidioxy-5,6-dihydro-14,15-dioxo-14,15-secocobyrinate, based on NMR-spectral data and since **4** is also formed cleanly in the corresponding low-temperature photooxygenation of **2b**. Catalytic reduction of the Co(III) complex **3** (H_2, Pt/C) in the presence of EDTA produces a colourless oil, from which the bicyclic fragments **5** (corresponding to rings A and D of **1**) and **6** (corresponding to rings B and C of **1**) are obtained in 99 and 91% yield, respectively, after chromatographic separation.

Introduction. – Recently, the action of singlet oxygen ($^1O_2$, [1]) on vitamin-B_{12} derivatives was examined in the photooxygenation of the dicyano-Co(III)-corrin cobester **1**

Scheme 1

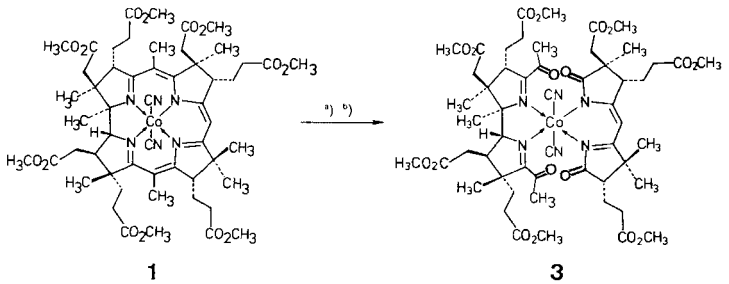


(= heptamethyl *Coα,Coβ*-dicyanocobyrinate [2]). It was found to provide a convenient and preparatively useful method for specific cleavage of the corrin macrocycle of **1** [3], which is apparently superior to the alternative of ozonolysis [4]. Methylene-blue(MB)-sensitized photooxygenation of **1** in MeOH solution at r.t. led to the isomeric secocobyrinates **2a** (heptamethyl *Coα,Coβ*-dicyano-5,6-dioxo-5,6-secocobyrinate) and **2b** (heptamethyl *Coα,Coβ*-dicyano-14,15-dioxo-14,15-secocobyrinate) in good yield [3] *(Scheme 1)*, the former of which *Inhoffen* and coworkers [4] had already prepared *via* ozonolysis.

In view of the value of low-temperature ozonolysis as a method of degradation of **1** to monocyclic and bicyclic fragments [5–7] for the purpose of tracing (radioactive) markers for the elucidation of the biosynthesis of vitamin B_{12} [6] [7], an investigation on the photooxygenolytic degradation of **1** was taken up. This revealed a mild and efficient method of double cleavage of the corrin macrocycle of **1**, useful for the degradation of **1** to bicyclic fragments. A related result was obtained earlier by *Inhoffen* and coworkers [8], where controlled ozonolysis of a suitable derivative of **1**, heptamethyl *Coα,Coβ*-dicyano-10-bromocobyrinate [9], furnished bicyclic ligand fragments in low yield.

Results and Discussion. – *Photooxygenation Experiments with* **1**. MB-sensitized photooxygenation of **1** (100 mg) at *ca.* – 45° in CD_3CN using visible light[1]) led to rapid consumption of the deep red Co(III)-corrin, then to the buildup of orange intermediates, and finally to the formation of yellow compounds. The reaction was easily followed by UV/VIS and TLC analysis. After 4.5 h, the TLC of the cold mixture indicated the presence of two yellow products. Upon warming the mixture to 40° (15 min), the less polar product disappeared and apparently converted into the other. Workup and chromatographic separation of the yellow product fraction from MB and from orange side-products furnished chromatographically pure heptamethyl *Coα,Coβ*-dicyano-5,6:14,15-tetraoxo-5,6:14,15-disecocobyrinate (**3**; 'tetraoxodiseco-cobester'[2]), *Scheme 2*) which was precipitated from benzene/hexane. This sample of **3** (after drying: 96.5 mg (91%) of yellow powder) was identical (^{1}H-NMR, UV/VIS, TLC) with the material produced by the corresponding photooxygenation of the secocobyrinate **2b** (see below).

Scheme 2



1 **3**

[a]) *hν* ($\lambda > 550$ nm), O_2 (1 atm), MB, CD_3CN_2 –47 °C. [b]) r.t.

[1]) See *Exper. Part* for further experimental details.

[2]) Systematic name of **3**: dicyano{dimethyl [2,2'-diacetyl-4,4'-bis(methoxycarbonylmethyl)-3,4',5'-trimethyl-[5,5'-bi-1-pyrrolin]-3,3'-dipropionate]}{4α-(2-(methoxycarbonyl)ethyl)-5-[4'α-(2-(methoxycarbonyl)ethyl)-3',3'-dimethyl-5'-oxo-1'-pyrrolin-2'-yl]methylidene-3β-methoxycarbonylmethyl-3α-methyl-2-oxopyrrolidin-1-ato}cobalt(III).

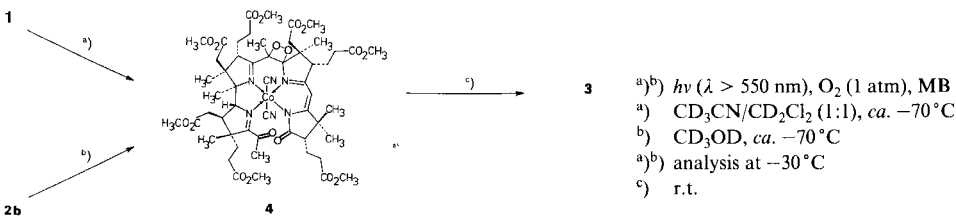
Further information on this double cleavage was obtained from investigations on the identity of the chemical intermediates during the low-temperature photooxygenolysis of **1.** As deduced from UV/VIS and TLC analysis of samples removed during the photooxygenation reaction and warmed to r.t., the disappearance of **1** was accompanied first by the formation of the secocorrinoid cleavage products **2a** and **2b**. An early interruption of the photooxygenation of **1** and analysis after workup at r.t. showed **1**/**2a**/**2b**/**3** in a ratio of 1.4:1:4:1.1. In a second stage of the low-temperature photooxygenation, more hypsochromically absorbing (yellow) products followed, apparently with a doubly cleaved corrin chromophore, which were converted to **3** as the final product after warming to r.t. However, analysis of the reaction mixture of the completed photooxygenation at low temperature by ^{1}H-NMR (at −30°) revealed the single secondary intermediate **4**, which was converted into **3** upon warming to r.t. (**4**→**3** (r.t., benzene): $t_{1/2}$ = *ca.* 30 min). The intermediate **4** was identified by comparison (^{1}H-NMR, CD_2Cl_2, −30°) with the product of low-temperature photooxygenation of **2b**, and was assigned the structure of a *Coα*,*Coβ*-dicyano-5,6-epidioxy-5,6-dihydro-14,15-dioxo-14,15-secocobyrinate.

The clean formation of **4** by photooxygenation of **1** at low temperature, which presumably proceeds in consecutive steps involving primary interruption of the corrin π-system at the 5,6-and the 14,15-positions, provides indirect evidence for the secondary photooxygenolytic cleavage of oxygenated intermediates[3]) that are transformed into the secocorrinoid products **2a** and **2b** during warm-up. The intermediate formation of corrin-dioxetanes[3]), their considerable stability, and ease of further photooxygenation at low temperature appears to be indicated by this result.

Photooxygenation of **2a** *and of* **2b**. MB-sensitized photooxygenation of **2a** in O_2-saturated CD_3CN at *ca.* −45° with visible-light[1]) irradiation led to a rapid consumption of the secocorrinoid **2a** (after 15 min, disappearance of *ca.* 80% of **2a** according to UV/VIS). The photolysis was stopped after 15 min and the mixture warmed up to r.t. and worked up by chromatography. The major product[4]), a yellow compound, was identified as **3** (comparison with **3** from photooxygenation of **2b**) by ^{1}H-NMR, UV/VIS, and TLC analysis. It was obtained in 32% yield (based on **2a** converted *(Scheme 1)*[5])).

Likewise, the MB-sensitized photooxygenation of **2b** in O_2-saturated CD_3OD at −50° with visible light proceeded quickly with formation of yellow products. After warm-up to

Scheme 3



[3]) Presumably a 5,6-epidioxy-5,6-dihydro-cobyrinate and a 14,15-epidioxy-14,15-dihydro-cobyrinate (as precursors of **2a** and **2b**, respectively).

[4]) Besides several non-identified yellow products.

[5]) Several other reaction conditions were tried (concerning solvent (*e.g.* CD_3OD) or temperature), but the yield of **2a**→**3** could not be improved.

r.t. and workup, 'tetraoxodiseco-cobester' **3** was isolated in 73% yield (93% with respect to **2b** converted *(Scheme 1)*[6]).

The constitution of the Co(III) complex **3**, plausible on the basis of its origin (**1**, **2a** or **2b**), was originally assigned based on UV/VIS, ^{1}H- and ^{13}C-NMR, and FAB-mass spectra. The sites of cleavage at the *meso*-positions 5(6) and (14)15 manifest themselves in a shortened chromophore (further hypsochromic shift of the maximum of the long-wavelength absorption band to 400 nm), appearance of signals due to 2 acetyl groups in the NMR spectra (^{1}H-NMR ($CDCl_3$): 2.48, 1.88 ppm (2*s*). ^{13}C-NMR ($CDCl_3$): 30.4, 33.3 ppm (2*q*); 2 low-field *s* (2 CH_3CO)), and complementary information from the FAB-MS (*e.g.*: M^+ at 1152, A–D fragment at 579, and Co-(B–C) fragment at 522). In addition, the presumed inplane arrangement of the bicyclic corrin fragments is supported by ^{1}H-NMR NOE difference sepctra[7]). The expected intact α-configuration of the propionate substituents at C(3) and at C(8) (as well as the cleavage sites at the 5,6- and 14,15-positions)[8]) is confirmed by the hydrogenolytic decomposition of **3** into the bicyclic ligand fragments **5** and **6** (see below).

The photooxygenation of **2b**, while leading to the single product **3** in high yield after warming to r.t. (or when the reaction is carried out at r.t.)[6]), produces initially, a second yellow compound, as revealed by TLC analysis of cold reaction mixtures. This thermal precursor of **3** (observed also for the cold reaction mixtures from photooxygenation of **1**) was found to be sufficiently stable at −30° to be analyzed by ^{1}H- and ^{13}C-NMR. Photooxygenolysis of **2b** at −70° in CD_3OD followed by workup at −30° allowed the isolation of this yellow compound, which was assigned the structure of the dioxetane **4** (see *Scheme 3*).

Its ^{1}H-NMR spectrum (CD_2Cl_2, −30°), in particular, exhibited 7 *s* at 1.09, 1.17, 1.23, 1.32, 1.45, 1.72, and 1.97 ppm (CH_3 groups bound to quaternary C-atoms, including CH_3–C(5) and 1 *s* (only) at 2.81 ppm (CH_3CO)). Similarly, the ^{13}C-NMR spectrum (CD_2Cl_2, −60°) of **4** showed *s*'s at 109.0 (C(6)) and 95.3 ppm (C(5)) due to the C-atoms[8]) of the (proposed) dioxetane ring [10].

The existence of a common intermediate **4** during photooxygenolysis of either **1** or **2b** and its clean conversion in solution to the bisected complex **3** upon warm-up to r.t. appear remarkable. While postulated [11] to be formed similarly in photooxygenation reactions of the related porphinoid compounds, to our knowledge, this provides for the first time evidence for such a dioxetane intermediate during photooxygenation of a tetrapyrrolic compound[9]). Its striking stability[10]) could be a consequence of the highly substituted periphery, similar to the presumed steric effect of α-alkyl substituents on the thermal stability of simple 1,2-dioxetanes [17], or it could be a manifestation of (geometric) constraints on its decomposition, due to the metal-chelating corrinoid ligand system.

In the formation of **3**, the sites of cleavage are the same as those of the primary fragmentation of **1** to **2a** and to **2b**. They are estimated to be the sites of highest

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[6]) In similar experiments carried out at r.t., **3** was obtained in *ca.* 73% yield (with respect to converted **2b**); *H. P. Jutzi*, diploma thesis, 1982.

[7]) Homonuclear ^{1}H-NMR NOE difference spectra indicated mutual spatial proximity of CH_3–C(5) and CH_3–C(7) as well as $CH_3(\beta)$–C(12) and CH_3–C(15)[8]) (see *Exper. Part* for details).

[8]) Numbering of C-centers according to their origin in **1** (see *Scheme 1*).

[9]) In addition, it shows the photooxygenation of cobyrinate **1** as well as of the secocobyrinate **2b** to involve a regio- and diastereoselective addition of $^1O_2$ to one face of the ligand system. Exploratory ^{1}H-NMR NOE difference spectra did not allow a stereochemical assignment (α or β) of the dioxetane function in **4**; chlorination [12] and hydroxylation [13] of **1** are thought to involve attack of the electrophile on the α- and on the β-face, resp.

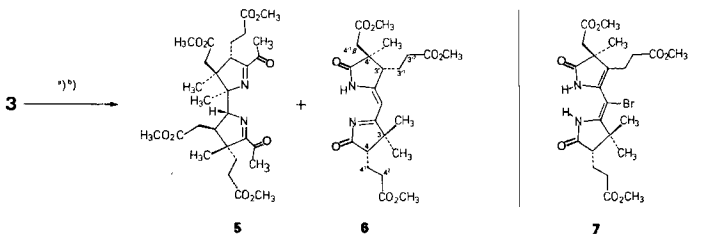
[10]) In contrast, the photooxygenation [14] of 'pyrocobester' (a *Co*α,*Co*β-dicyano-B-didehydrocobyrinate obtained by thermolysis of **1** [15]) at low temperature does not lead to intermediates (as precursors of the product of photooxygenolysis '5,6-dioxo-5,6-seco-pyrocobester' [16]) that are stable and detectable by ^{1}H-NMR at −60°; unpublished work.

nucleophilic reactivity of the corrinoid ligand π-system [18][11]). From analysis of the earlier stage of photooxygenation at low temperature, where **2b** is formed preferentially over **2a** in CD_3CN, while **2a** and **2b** are formed in a *ca.* 2:1 ratio in MeOH solution (at r.t.), the reactivity of the 5(6)- and the (14)15-positions for the electrophilic attack by $^1O_2$ can be inferred to be comparable. As concerns the second cleavage step, the first interruption of the corrin macrocycle to a dioxosecocorrin or to a hypothetical epidioxy-dihydrocorrin apparently does not strongly alter the patterns of the regioselectivity towards further photooxygenation, compared to the original corrin system. However, in MeOH solution[12]), **2a** and **2b** are photooxygenated *ca.* 10 and 5 times slower, respectively, than **1**.

A large H/D-solvent-isotope effect on the rate of MB-sensitized photooxygenation of **2b** (it proceeds with relative rates of 17.6:2.6:1, when carried out in CD_3OD, CH_3OD, and CH_3OH, resp.)[12]) allows the characterization of the involvement of $^1O_2$ [1] in this reaction. Similarly also, under the conditions described[1]), the photooxygenolytic degradation of **1** to **3** (or to **4**) proceeds about twice as fast in CD_3CN as in CH_3CN.

Hydrogenolytic Cleavage of **3**. In the second step, the Co(III) complex **3** was cleaved into the bicyclic A–D and B–C fragments **5** [8] and **6** by demetallation. Stirring of a deoxygenated mixture consisting of **3** (40 mg), an excess of EDTA, and a Pt/C catalyst in MeOAc/MeOH/H_2O 4:1:1 for 40 min at r.t. under H_2 led to decoloration of the mixture. After neutral workup at 0°, two products could be separated by chromatography as colourless oils. The less polar (20.0 mg, 99% yield) proved identical (^{1}H- and ^{13}C-NMR, IR, MS) with the A–D fragment **5** (dimethyl 2,2′-diacetyl-4,4′-bis(methoxycarbonylmethyl)-3,4′,5′-trimethyl-[5,5′-bi-1-pyrroline]-3,3′-dipropionate) described by *Inhoffen* and coworkers [8] and was obtained in 99% yield *(Scheme 4)*. The more polar, colourless

Scheme 4



a) H_2, Pt/C, r.t. b) MeOAc/MeOH/H_2O 4:1:1, EDTA

compound (14.7 mg, 91% yield), which decomposed slowly on storage at −20°, was spectroscopically determined (^{1}H- and ^{13}C-NMR, UV/VIS, CD, MS, IR) to be a single isomer of the complementary B–C fragment **6** (methyl 2-[3′α-(2-(methoxycarbonyl)ethyl)-4′β-methoxycarbonylmethyl-4′α-methyl-5′-oxopyrrolidin-2′-ylidene]methyl-3,3-dimethyl-5-oxo-1-pyrroline-4α-propionate; see *Scheme 4*). Its ^{1}H-NMR spectrum (vinylic H-atom, weakly split ($J \approx 0.7$ Hz) by the allylic H–C(3′)) and its ^{13}C-NMR spectrum (1 olefinic, 2 lactam and 2 imine C-atoms) are fully consistent only with the linearly conjugated system, as similarly encountered earlier for various bicyclic inter-

[11]) Based on '(atomic) localization energies' as obtained, *e.g.*, from *Hueckel*-MO calculations [19].

[12]) Experimental conditions: initial concentration of **1**, **2a** or **2b**: $1.8 \cdot 10^{-3}$M; concentration of MB: $2.02 \cdot 10^{-4}$M; monochromatic irradiation at 650 nm ($OD_{650} = 1.8$); 20 ± 2°; O_2 (1 atm); linear plot $\log(OD/OD_0)$ *vs.* time.

mediates in the total synthesis of vitamin B_{12} [20]. This finding of a linearly conjugated π-system in **6** contrasts with the structure of the bromo derivative **7** [8] (see *Scheme 4*), for which *Inhoffen* and coworkers determined a tautomeric, cross-conjugated π-system. Apparently, the preference for this bis-enaminoid tautomer is a peculiarity of **7**, induced by the bromo substituent at the *meso*-position. Indeed, ^{1}H-NMR NOE difference spectra of **6** also confirmed the expected intact α-configuration of the propionic-acid side chain of ring B[13]).

Decomposition of the bisected dicyano-Co(III) complex **3** occurs readily upon reduction of the inert [21] Co(III) center (presumably to Co(II)). In the presence of EDTA, reductive decomposition of **3** sets free both bicyclic ligand fragments (**5** and **6**) in one operation, which is thought to involve the extrusion of the Co(II) ion from its complex with the bislactam **6** by EDTA in a second chemical step. In the absence of EDTA, it leads to the bicyclic ligand fragment **5** and presumably to a Co(III) complex of the bislactam **6** (a paramagnetic yellow compound with an intense band at 361 nm and a weak band at 450 nm, similar to that found for a Co(II) complex of a synthetic bicyclic corrin fragment [20a]). Addition of EDTA to a solution of this paramagnetic degradation product of **3** under N_2 leads to its decoloration and to liberation of **6** in a somewhat reduced yield (77%).

Conclusions. – The photooxygenolysis of **1**, followed by demetallation of the photooxygenation product **3**, provides the bicyclic fragments **5** and **6** in over 80% yield each. This method of degradation, therefore, opens an economic route to intact bicyclic fragments, derived from vitamin B_{12} which are of interest in the context of biosynthetic studies [5] [6] and as chiral bicyclic ligands for metal complexes [5b] [20][14]).

The present work extends the results from mechanistic [14] and preparatively [3] [16] oriented investigations on the photooxygenolytic cleavage of vitamin-B_{12} derivatives to dioxosecocorrinoids to the stage of further degradation of the corrin macrocycle to bicyclic ligand fragments. It broadens the scope of the photooxygenolysis as a highly selective and easily performed method of degradation, demonstrated with the lipophilic vitamin-B_{12} derivative cobester (**1**). As before [3] [14], the presumed involvement of $^1O_2$ is supported by a sizeable H/D-solvent-isotope effect [1] here also. In addition, the sites of attack by $^1O_2$ (generated by MB photosensitization) correlate with the positions (5 and 15) of highest reactivity towards electrophiles [18] [22] of the corrinoid π-systems. In agreement with the electrophilic nature of the oxygenating species, the reduced efficiency of the secondary cleavage of **2a** and **2b** by $^1O_2$ could (in part) be an effect of their electron-withdrawing carbonyl groups.

As can be inferred from the available information, the oxygenation not only proceeds with pronounced regioselectivity, but, at C(5), presumably also stereoselectively[9]), reflecting the difference of reactivity of the diastereofaces of the corrin π-system of vitamin-B_{12}

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[13]) In ^{1}H-NMR NOE difference spectra ($CDCl_3$, 300 MHz, δ(TMS) = 0 ppm) of **6**, the enhancements of signals resulting from irradiation at the frequency of the *s* at 1.16 ppm ($CH_3(4'^1\alpha)$) were strong for an *AB*-system at 2.58/2.81 ppm (J = 17), assigned to $CH_2(4'^1\beta)$, and for 2 *m* at *ca.* 1.85 ppm and *ca.* 2.5 ppm (presumably due to $CH_2(3'^1)$ and $CH_2(3'^2)$), but were barely detectable for the signal at 3.23 ppm (*dd*, CH(3')).

[14]) Indeed, the further degradation of the A–D fragment **5** to monocyclic compounds was recently carried out for the former purpose [6]. Further cleavage of the B–C fragment **6** by photooxygenation appears feasible, but has not yet been investigated. However, controlled ozonolytic degradation of bicyclic ligand fragments similar to **6** there represents a known alternative method already [5b].

derivatives. In summary, the photooxygenation of vitamin B_{12} [23] and of lipophilic vitamin-B_{12} derivatives [3] [16] yields specific cleavage products of the corrin macrocycle in a preparatively useful way and appears of particular interest concerning information on the reactivity patterns of the corrin macrocycle. Such prospects[15]) should also encourage investigations on the reaction of $^1O_2$ with other (porphinoid) natural products.

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Experimental Part

1. General. Solvents and reagents: CH_3OH: *Fluka puriss. p.a.;* CH_3OD: *Fluka puriss. p.a.*, > 99.8% D; CD_3OD: *Fluka puriss.*, > 99.8% D; CD_2Cl_2: *Fluka purum*, > 99.5% D; CD_3CN: *Fluka purum*, > 99.5% D; MeOAc, CH_2Cl_2, benzene: all practical grade and redistilled; silica gel: *Merck Kieselgel 60* No. *9385;* cobester **1** [2]: purified by column chromatography and by crystallization; 5,6-dioxo-5,6-seco-cobester **2a** [4] and 14,15-dioxo-14,15-seco-cobester **2b** prepared as described in [3]; methyleneblue (MB): see Ph. Hv.; ethylenediamine-tetraacetate tetrasodium salt (EDTA): *Fluka pract.;* $Na_2Cr_2O_7$: techn. grade; 5% Pt/C: *Fluka puriss.;* H_2: *Stickstoff-Wasserstoffwerke*, Luzern. TLC on plates coated with silica gel *60*, *Merck* Art. 5271. UV/VIS (CH_3OH): *Perkin Elmer PE 555;* λ_{max} (log ε) in nm, min. = λ_{min}; *OD* = optical density. CD (CH_3OH): *Jobin-Yvon Mark III;* λ of extrema and of the zero passages λ_0 in nm (molar decadic circular dichroism [$\Delta\varepsilon$]). IR ($CHCl_3$): *Perkin Elmer PE 125;* in cm^{-1}. ^{1}H-NMR: *Bruker WM-300;* in $CDCl_3$ (unless specified otherwise); 300.14 MHz; TMS internal reference (= 0 ppm); NOE difference spectra in $CDCl_3$ (degassed): irr. = irradiation, enh. = enhancement, *w* = weak, *m* = medium, *s* = strong. ^{13}C-NMR ($CDCl_3$): *Bruker WM-300;* 75.47 MHz; TMS internal reference (= 0 ppm); multiplicities from off-resonance-decoupled spectrum. MS: *Hitachi Perkin Elmer RMU-6M*. FAB-MS: *Kratos AEI MS-50* fitted with *M*-scan FAB-system; matrix: NPOE (o-nitrophenyl-n-octyl-ether); Xenon, 8.3 eV.

2. Apparatus and Experimental Set-up. The photolysis cell used is described in [3]. In the experiments reported here, an O_2 pressure of 1 atm was maintained by a slow stream of O_2 through the reaction soln. For irradiation at r.t., the photolysis cell was immersed into a filter/cooling system described in [3]. For low-temp. irradiations, the photolysis cell was cooled externally. The light was filtered by a soln. of $Na_2Cr_2O_7$ (0.5M) in distilled H_2O, to cut off light of $\lambda < 550$ nm [25]. A 15V/150W W-lamp (*BLV, Licht- und Vakuumtechnik*, F.R.G.) with ellipsoidal mirror was placed in front of the photolysis cell to illuminate the photolysis soln. horizontally and evenly through the *Pyrex* window of the cell (and through the filter/cooling solns.). The concentration of MB was chosen to give an *OD* of *ca.* 2 (at 650 nm) initially.

3. Experimentally Procedures. 3.1. Tetraoxodiseco-cobyrinate **3**[2]) *by Sensitized Low-Temperature Photooxygenolysis of Cobester* **1**. A soln. of 100 mg (91.8 μmol) of crystalline **1** and 0.11 mg (0.34 μmol) of MB in 2.5 ml of CD_3CN was introduced into the photolysis cell under O_2. The contents of the cell were purged with a slow stream of O_2, while it was positioned into the cooling bath at −47°. Then, the soln. was illuminated evenly with the filtered light of the 150-W halogen lamp. The progress of the photolysis was followed by withdrawing and analyzing (TLC and UV/VIS) small samples of equal volume at 1-h intervals. At the same times, 0.11 mg of MB in 0.3 ml of CD_3CN were added to compensate for loss of sensitizer/solvent. After 4.5 h, the photolysis was stopped and the solvent evaporated at 40° *in vacuo* (15 min). The residue was chromatographed on TLC (4 plates, 20 × 20 cm) with benzene/MeOAc 1:4, to which 0.5% MeOH (containing 3% HCN) were added. The yellow main fraction[16]) was eluted with CH_2Cl_2/MeOH 3:1, the org. solns. were washed with dil. aq. $NaHCO_3$ soln., dried by filtration through a plug of dry cotton wool, and evaporated at r.t. *in vacuo*. The residue was taken up in *ca.* 2 ml of benzene and precipitated by *ca.* 20 ml of hexane to give (after drying under high vacuum, r.t., 3 h) 96.5 mg of **3** (91%) as a yellow powder, which was identified (TLC, ^{1}H-NMR, UV/VIS) with **3**[2]) prepared earlier by photooxygenation of **2b** (see below).

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[15]) Photooxygenation reactions have already been found useful, *e.g.*, for the selective degradation of chlorophyll derivatives [24].

[16]) Several redish fractions were also present, but not analyzed.

3.2. Tetraoxodiseco-cobyrinate **3**[2]) *by MB-Sensitized Photooxygenation of 14,15-Dioxo-14,15-secocobyrinate* **2b**. A soln. of 45.0 mg (40.1 μmol) of crystalline **2b** and 0.11 mg of MB (0.34 μmol) in 2.5 ml of CD_3OD was introduced into the photolysis cell under O_2. After saturation of the soln. with O_2, the photolysis was carried out at −50° (external cooling) for 110° min, and otherwise as described in *3.1*. Workup of the mixture as described above (but using 3 TLC plates only) allowed to isolate 33.9 mg (73%) of **3** as a yellow powder, besides 9.5 mg of **2b** (21%). Compd. **3** was characterized as follows: TLC (benzene/MeOAc/MeOH (1% HCN) 19:80:1) R_f 0.22. M.p. 118° (dec.) UV/VIS ($c = 1.31 \cdot 10^{-5}$M): 219 (4.54), 267 (4.14), 320 (3.70), 400 (3.99). CD ($c = 1.31 \cdot 10^{-5}$M): 220 (10.2), 235 (−19.7), 264 (9.10), 308 (−7.21), 395 (−5.31), 433 (22.4); λ_0 at 225, 250, 286, 408. IR (5%): 2130*w*, 1730*s*, 1635*w*, 1602*w*, 1543*m*, 1502*m*, 1437*s*, 1407*m*, 1355*m*, 1105*s*, 1083*s*, *etc.* ^{1}H-NMR[8]): 1.05, 1.18, 1.22, 1.24, 1.27, 1.29 (6*s*, 6 CH_3); 2.50, 2.88 (2*s*, 2 CH_3CO) overlapped by 1.6–3.1 (*m*), in total 29H; 3.23 (*dd*, $J = 6$, H–C(13)); 3.53, 3.66, 3.67, 3.69, 3.72, 3.725, 3.76 (7*s*, 22H, 7 $COOCH_3$, +1H); 4.03 (*d*-like, H–C(3)); 5.87 (*s*, H–C(10)); 6.11 (*d*, $J = 7$, H–C(19)). ^{1}H-NMR NOE[8]): irr. 5.88 (H–C(10)): enh. 3.23*s* (*dd*, H–C(8)); irr. 2.88 (CH_3–C(15)): enh 1.05*w*, (*s*, $CH_3(\beta)$–C(12)?) and 1.25*w* (*s*, CH_3–C(17)?); irr. 2.50 (CH_3–C(5)): enh. 4.03*s* (*d*, H–C(3)) and 1.18*w* (*s*, CH_3–C(7)); irr. 1.18: enh. 2.50*s*; irr. 1.05: enh. 2.55*s* (*m*, H–C(13)?), 1.92*m* (*m*, ?), and 2.88*m*. ^{13}C-NMR[8]): 15.5, 17.1, 19.6 (3 *q*); 20.8 (*t*); 21.8, 21.9 (2 *q*); 23.8, 26.7 (2*t*); 27.1 (*q*); 29.3 (*t*); 30.4 (*q*); 31.7, 32.0, 32.3, 33.1 (4*t*); 33.3 (*q*); 34.7 (*t*); 39.0 (*d*, C(18)); 40.7, 43.0 (2*t*); 44.1, 45.6, 48.2 (3*s*, C(2), C(7), C(12)); 50.2 (*d*); 51.1, 51.5, 51.6, 51.8 (3-fold int.), 52.1 (5*q*, 7 $COOCH_3$); 52.4 (*d*); 59.1 (2*d*, C(3), C(8)?); 62.1 (*s*, C(17)); 82.9 (*d*, C(19)); 88.4 (*s*, C(1)); 102.8 (*d*, C(10)); 128.8, 132.2 (2*s*, CN); 170.5, 171.8, 171.9, 172.3, 172.4, 173.6, 173.9 (7*s*, 7 $COOCH_3$); 183.9, 184.1, 186.6, 189.1, 189.4, 190.5 (6 *s*); 192.7, 199.0 (2*s*, C(5), C(15)). FAB-MS: 1153 (3), 1152 (4, M^+), 1127 (6), 1126 (16), 1125 (31, $M^+ - 27$ (HCN)), 1124 (26), 1101 (5), 1100 (14), 1099 (20, $M^+ - 53$ (HCN, CN)), 1098 (5), 1071 (7), 1070 (20), 1069 (34, $M^+ - 83$), 1011 (41), 734 (16), 619 (11), 580 (34), 579 (100, A–D fragment), 578 (21), 523 (11), 522 (38, Co-(B–C) fragment), *etc.*

3.3. Tetraoxodiseco-cobyrinate **3**[2]) *by MB-Sensitized Photooxygenation of the 5,6-Dioxo-5,6-secocobyrinate* **2a**. A soln. of 51 mg (45 μmol) of **2a** and 0.11 mg of MB (0.34 μmol) in 2.5 ml of CD_3CN were introduced into the photolysis cell under O_2. The photolysis was carried out as described in *3.1*, but at −45° (external cooling) and for 15 min only. Workup as described in *3.1*, with chromatography on 3 TLC plates (developing soln.: CH_2Cl_2/CH_3OH 19:1), resulted in 14.5 mg (32%) of **3** (TLC, UV/VIS, ^{1}H-NMR), 6.1 mg (12%) of **2a** and 9.9 mg and 2.3 mg of unidentified, polar, yellow products.

3.4. Heptamethyl Coα,Coβ-*Dicyano-5,6-epidioxy-5,6-dihydro-14,15-dioxo-14,15-secocobyrinate* (**4**) *by MB-Sensitized Photooxygenation of* **2b** *at Low Temperature. Experiment A.* A soln. of 30 mg (26.7 μmol) of crystalline **2b** and 0.1 mg (0.31 μmol) of MB in 1.5 ml of CD_3OD was introduced into the photolysis cell under O_2. With external cooling at −70°, the mixture was irradiated (as described in *3.1*) for 3 h and then transferred into a flask at −70° under N_2. Then, the mixture was diluted with 2 ml of cold CH_2Cl_2 and applied to a column (silica gel, 5 g; $l \approx 15$ cm; $\varnothing \approx 2$ cm; external cooling at −70°). The yellow product fraction was eluted with CH_2Cl_2/CH_3OH 32:1 at −70° (and thereby separated from small amounts of **2b** and from MB) and evaporated at −30° under high vacuum. The residue was taken up in cold CD_2Cl_2 and dried at −30° (high vacuum)[17])[18]). ^{1}H-NMR (CD_2Cl_2, −60°, 300 MHz): 1.05, 1.13, 1.20, 1.30, 1.43, 1.69, 1.96 (7*s*); 2.79 (*s*, CH_3CO) overlapped by 1.5–3.3 (*m*); 3.55, 3.57, 3.59, 3.597, 3.60, 3.63, 3.67 (7*s*, 7 $COOCH_3$); 4.70 (*d*, $J = 7$, H–C(19)); 5.15 (*s*, H–C(10)). ^{13}C-NMR (CD_2Cl_2, −60°, 75 MHz): 16.1, 17.7 (2*q*); 19.8 (*q*, double intensity); 20.9 (*t*); 21.6, 24.3 (2*q*); 25.5 (*q*,*t*); 26.7, 30.9, 31.6, 32.4, 32.5, 33.4 (6*t*); 33.5 (*t*,*q*) 37.4 (*d*); 38.7, 41.5 (2*t*); 46.4, 47.9 (2*s*); 50.8 (*d*); 51.0 (*s*); 52.8 (*q*); 53.0 (*q*, double intensity); 53.05, 53.2, 53.3, 53.7 (4*q*); *ca.* 54.6 (*d*?) (overlapped by 54.3, 54.6, 55.0, 55.3, 55.7 (CD_2Cl_2)); 56.2 (*d*); 63.2 (*s*); 80.5 (*d*); 86.8 (*s*); 92.6 (*d*); 95.3, 109.0 (2*s*); 134.0, 134.7, 172.0 (3*s*); 172.2 (*s*, double intensity); 173.2, 174.1, 174.2, 175.2, 180.5, 183.1, 183.8, 184.6, 192.0, 199.6 (10*s*).

Experiment B. A soln. of 5.5 mg (4.9 μmol) of crystalline **2b** and 0.15 mg (0.47 μmol) of MB in 1.5 ml of CD_3OD were photooxygenated as described in *3.4, Exper. A*, for 3 h. The mixture then was transferred into a flask precooled to −30° under N_2. The solvents were evaporated at < −30° (high vacuum), the yellow residue was dissolved in 0.5 ml of cold CD_2Cl_2 (at −30°), transferred into an NMR tube of −30°, and the spectrum recorded. ^{1}H-NMR (CD_2Cl_2, −30°): 1.09, 1.17, 1.23, 1.32, 1.45, 1.72, 1.97 (7*s*); 2.81 (*s*) overlapped by 1.5–2.9 (*m*) in total 38H; 3.01 (*dd*, $J = 8, 4$) and 3.07 (*d*, $J = 15$), together 2H; 3.59, 3.61, 3.62, 3.63, 3.64, 3.65, 3.70 (7*s*, $COOCH_3$); 3.77

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[17]) Exploratory UV/VIS spectra with a sample of **4** prepared and purified similarly as described here indicated only a small bathochromic shift (401→405 nm) of the long-wavelength absorption maximum upon storage in benzene at r.t., corresponding to the thermolysis **4**→**3**.

[18]) Warm-up of the combined samples of **4** after NMR analysis, followed by chromatographic purification (see *3.1*), allowed isolation of 27.7 mg (24.1 μmol) of **3** as a yellow powder, identified (^{1}H-NMR, UV/VIS, TLC) with **3** from *Exper. 3.2*.

(*t*-like, 1H); 4.75 (*d*, *J* = 8, 1H); 5.19 (*s*, 1H)[19]). Then, the sample was allowed to warm to r.t. and was stored in the dark at r.t. overnight. The ^{1}H-NMR[19]) then indicated complete conversion of **4** into **3**.

3.5. Compound **4** *by MB-Sensitized Photooxygenation of Cobester* **1** *at Low Temperature.* A soln. of 10 mg (9.1 μmol) of **1** and 0.15 mg (0.46 μmol) of MB in 1.5 ml of CD_2Cl_2/CD_3CN 1:1 was introduced into the photolysis cell under O_2 and irradiated (as described in *3.1*) with external cooling at –70°. After 3 h, the cold mixture was transferred into a precooled round-bottom flask (at –30°) and evaporated to dryness at –30°. The residue was dissolved in cold CD_2Cl_2 and transferred into a NMR tube at –30°. The ^{1}H-NMR of this soln.[19]) at –30° agreed with that of **4** obtained from **2b** (see *3.4, Exper. B*). Warm-up and storage of the mixture in the NMR tube at r.t. over night gave **3**, as judged from ^{1}H-NMR[19]), UV/VIS and TLC.

3.6. Bicyclic Ligand Fragments by Catalytic Reductive Cleavage of **3**. A soln. of 40 mg (34.8 μmol) of **3** in 24 ml of MeOAc was treated with 12 mg of 5% Pt/C and with a soln. of 360 mg (950 μmol) of EDTA in 12 ml of H_2O/CH_3OH 1:1, which had been acidified to pH 6.4 with AcOH. The mixture was freed of air by repeated evacuation and flushing with H_2 (3×) and then allowed to react at r.t. under H_2 (slightly above 1 atm) for 40 min, during which time the original yellow colour of the starting material faded completely. Then, the mixture was shaken quickly with 20 ml of sat. aq. $NaHCO_3$ soln. containing crushed ice. The org. layer was filtered through a plug of cotton wool and evaporated to dryness at 0°. The residue was applied to a cooled column (40 g of silica gel *60*; ∅ ≈ 2 cm; MeOAc/Et_2O 1:5) and eluted with MeOAc/Et_2O 1:5. The 2 product fractions were collected at 0°, evaporated at 0°, and analyzed by TLC to be uniform. Compds. **5** (first eluted) and **6** were obtained as colourless oils. Drying (high vacuum, 2 h, r.t.) gave 20.0 mg (99%) of **5** and 14.7 mg (91%) of **6**. *Dimethyl 2,2'-diacetyl-4,4'-bis(methoxycarbonylmethyl)-3,4',5'-trimethyl-[5,5'-bis-1-pyrroline]-3,3'-dipropionate* (**5**): TLC (Et_2O/MeOAc) 2:1) R_f = 0.69. UV/VIS ($c = 7.87 \cdot 10^{-5}$M): 215 (3.84), 283 (sh, 2.28). CD ($c = 7.87 \cdot 10^{-5}$M): 226 (–30.7), 270 (5.58); λ_0 at 254. IR (5%), MS, ^{1}H and ^{13}C-NMR as described for **5** in [8].

Methyl 2-[3'α-(2-(methoxycarbonyl)ethyl)-4'β-methoxycarbonylmethyl-4'α-methyl-5'-oxopyrrolidin-2'-ylidene]methyl-3,3-dimethyl-5-oxo-1-pyrroline-4α-propionate (**6**): TLC (Et_2O/MeOAc 2:1) R_f 0.53. UV/VIS ($c = 7.82 \cdot 10^{-5}$M; EtOH): 212 (3.89), 318 (sh, 4.06), 332 (4.16), 345 (sh, 4.10). CD ($c = 5.86 \cdot 10^{-5}$M; EtOH): 222 (–11.4), 283 (0.6), 330 (sh, 0.3), 360 (–0.1), 395 (0.1); λ_o = 258, 350, 368[20]). IR (5%): 3430*w*, 3020*s*, 2970*m*, 2960*s*, 1735*s*, 1617*s*, 1500*s*, 1439*s*, 1382*m*, 1357*m*, 1317*m*, *etc.* ^{1}H-NMR ($CDCl_3$, 0°): 1.16 (*s*, $CH_3(4'^1\alpha)$); 1.19, 1.34 (2*s*, $CH_3(3\alpha)$, $CH_3(3\beta)$); 1.80–1.98 (*m*, 3H, $CH_2(4^1)$, $CH_2(3'^1)$); 2.10–2.25 (*m*, 1H, $CH_2(3'^1)$); 2.29 (*t*-like, H–C(4)); 2.40–2.60 (*m*, $CH_2(3'^2)$) overlapped by 2.59/2.83 (*AB*, J_{AB} = 17, $CH_2(4'^1\beta)$), overlapped by 2.66/2.83 (*ABXY*, J_{AB} = 17, $J_{AX} \approx J_{AY} \approx J_{BX} \approx J_{BY} \approx 7$, $CH_2(4^2)$); 3.24 (*dd*, *J* = 9.4, H–C(3')); 3.65, 3.69, 3.72 (3*s*, 3 $COOCH_3$); 5.45 (*s*, vinyl-H). ^{13}C-NMR ($CDCl_3$): 19.7 (*q*); 21.3, 23.2 (2*t*), 23.8, 26.2 (2*q*); 31.7, 32.4 (2*t*); 41.2 (*t*); 45.0, 46.2 (2*s*, C(4'), C(3)); 49.4, 50.1 (2*d*, C(3'), C(4)); 51.6, 51.8, 51.9 (3*q*, 3 $COOCH_3$); 89.5 (*d*, *meso*-C); 171.2, 172.8, 173.5 (3*s*, 3 $COOCH_3$); 182.0, 185.0 (double intensity), 189.0 (3*s*, 2 lactam *C*O's and 2 imine C-atoms). MS: 465 (17), 464 (24, M^+), 449 (4), 434 (4), 433 (16), 405 (3), 393 (4), 392 (23), 391 (100, $M^+ - 73$ ($C_3H_5O_2$)), 377 (7), 360 (7), 359 (29), 345 (4).

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[19]) The ^{1}H-NMR, in addition, exhibited signals at 1.12 (*d*, *J* = 6) and 3.94 ppm (*sept.*, *J* = 6) due to traces of i-PrOH and at 1.85 ppm (br. *s*, *ca.* 6H) due to H_2O.

[20]) Slight decomposition of **6** during the recording presumably caused the development of shoulders at 352 and 376 nm with $\Delta\varepsilon$ = –0.08 and 0.14, resp. (assignment based on experience from earlier experiments).

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