Oscillating chemical reactions, in which concentrations of species show a regular periodic increase and decrease, have been the focus of much scientific interest during the last decades. In Nature, oscillations are also known to occur, e.g., in enzymatic reactions like glycolysis, the peroxidase-oxidase reaction, and reactions of immobilized acetylcholine esterase and papain. While the glycolytic reaction is characterized by a complex degree of coupled enzymatic cycles, the aerobic oxidation of NADH catalyzed by the enzyme peroxidase-oxidase is the best understood, homogeneous oscillatory single enzyme system known so far. Oscillatory behavior in synthetic enzyme models has not been previously reported. Such models might provide insight into the factors that are responsible for the oscillations in natural systems.

We report here that a membrane-bound cytochrome P-450 enzyme mimic (Figure 1) exhibits oscillating behavior in the reduction of manganese(III) porphyrin. Previously we showed that the rhodium complex 2 is an efficient catalyst for the reduction of manganese porphyrin 1 by sodium formate. This system is capable of epoxidizing alkenes in the presence of molecular oxygen with turnover numbers that lie in the same range as those observed in Nature.

Manganese porphyrin 1 and rhodium complex 2 were incorporated into zwitterionic 1,2-dipalmitoylphosphatidylcholine (DPPC) in the same way as reported previously. Gel permeation chromatography showed that the porphyrin and the rhodium complex were bound to the bilayers of the vesicles. Furthermore, it was shown that the structure of the vesicles as observed by electron microscopy and the phase transition temperature of the bilayers (38 °C, differential scanning calorimetry) was not affected by the incorporation of 1 and 2. Fluorescence spectroscopic investigations as reported previously revealed that the porphyrin moieties were not aggregated at the porphyrin to lipid ratios used in the present study.

In an initial series of experiments, we investigated the influence of the concentration of formate ions and the rhodium complex, as well as the effect of the temperature, upon the reduction of the porphyrin. Oscillations in the concentration of manganese(II) porphyrin were found to be linear with the rhodium concentration; e.g., for \([\text{Rh}]:[\text{Mn}] = 10:1, \text{and for } [\text{Rh}]:[\text{Mn}] = 10:1, k_0 = 120 \pm 10 \text{ mol} \cdot \text{L}^{-1} \cdot \text{s}^{-1}\). The reduction rate of 1 varied linear with the rhodium concentration; e.g., for \([\text{Rh}]:[\text{Mn}] = 1:1, k_0 = 12 \pm 2 \text{ mol} \cdot \text{L}^{-1} \cdot \text{s}^{-1}\), and for \([\text{Rh}]:[\text{Mn}] = 10:1, k_0 = 120 \pm 10 \text{ mol} \cdot \text{L}^{-1} \cdot \text{s}^{-1}\).

So far all reduction experiments have been carried out under an argon atmosphere. In air at 48 °C and at a formate concentration of 0.25 M the reduction of manganese(III) porphyrin could not be observed at \([\text{Rh}]:[\text{Mn}] < 10:1\). Under aerobic conditions the reoxidation of the manganese(II) porphyrin is considerably faster than its reduction. At ratios \([\text{Rh}]:[\text{Mn}] > 10:1\), however, net reduction of 1 took place. Oscillations in the concentration of manganese(II) porphyrin were detected at \([\text{Rh}]:[\text{Mn}] = 10:1\), as illustrated in Figure 2. After

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Figure 1. Schematic representation of the cytochrome P-450 mimic and the redox couples and components.
an induction time of ca. 30 min, the manganese(II) porphyrin (UV–vis $\lambda_{\text{max}}$ 435 nm) was gradually formed; and ca. 50 min after the start of the experiment, the onset of oscillations with an oscillatory period of ca. 90 s was observed. When the Mn(III) species was monitored, a complementary retrogression curve was obtained, which indicates that the manganese porphyrin shuttles between the +2 and the +3 oxidation state. A semi-batch reactor with an oxygen-selective Clark electrode was used to measure the oxygen concentration in solution. At the start of the experiment the concentration of oxygen was 5.2 mg/L, which dropped to almost 0 when the Mn(II) species was formed. Changes in temperature caused the oscillations to cease, since both the reduction and the oxidation reactions are temperature dependent.

At an O$_2$/N$_2$-gas flow containing 1% oxygen, oscillations were not observed; instead, the manganese(II) porphyrin concentration was found to increase linearly with time. When this concentration had reached its maximum, both the B-band and the Q-band of the porphyrin were found to be shifted bathochromically by 5 nm. This may indicate that after reduction the porphyrin molecules move to a part of the bilayer that has a different polarity. Earlier studies by our group proved that manganese(II) porphyrin is located in the middle of the vesicle bilayer and oriented parallel to the bilayer normal. The charged manganese(III) porphyrin is probably situated at the bilayer/water interface. We tentatively propose that, upon reduction, I moves more to the middle of the bilayer. These alterations may lead to small changes in the bilayer packing, which in turn will change the local oxygen concentration. This mechanism may account for the onset of the oscillations.

In summary, we have presented the first example of an oscillation reaction in an enzyme model system. Calculations and further experiments are in progress in order to elucidate the underlying factors causing the oscillatory behavior.

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