Mössbauer Studies on Protoporphyrin IX Iron(II) Frozen Solutions Containing Ligands that cause the Iron to be in a Five Coordinate High Spin Iron(II) Environment

J. SILVER*, B. LUKAS and G. AL-JAFF

Department of Chemistry, University of Essex, Wivenhoe Park, Colchester CO4 3SQ, Essex, U.K.

Received June 14, 1983

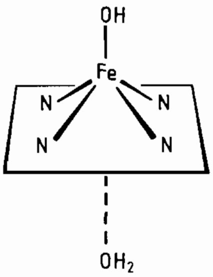
Mössbauer parameters are presented for a number of protoporphyrin IX iron(II) complexes containing ligands that allow the iron to be in a five coordinate high spin iron(II) electronic environment. Such environments are characterised by large quadrupole splittings in the range 4.0 to 4.4 mm s^{-1}. These compounds have characteristic electronic spectra.

The implications of catechol type ligands binding protoporphyrin IX iron II/III moieties are discussed.

Introduction

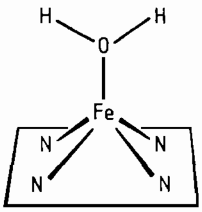
Since the report of our studies [1] on frozen solutions of protoporphyrin IX iron(II) in the pH range 7–14, in which we presented Mössbauer data for the presence of a protoporphyrin IX containing high spin iron(II) five coordinate site with a hydroxide as the fifth ligand, the crystal structure and Mössbauer parameters for $[Fe(TP_{piv}P)Cl]^-[KC222]C_6H_5Cl$ have been reported [2]. This structure contains a five coordinate iron(II) site with the chloride ion being in the axial position inside the cavity formed by the pivalamide arms of the picket fence porphyrin. The iron atom lies above the 24 atom core mean plane by 0.593 Å. The displacement of iron out of the 4N plane is the largest observed so far in high spin iron(II) porphyrin derivatives [3]. The Mössbauer data for this site are very similar to that which we reported for the five coordinate site where hydroxide was the fifth ligand [1].

The structure of $[Fe(SC_6HF_4)TP_{piv}P][NaC_{12}H_{24}O_0]$ has also been reported [2]. Here the high spin iron(II) is also in a five coordinate environment but in this the fifth ligand (the thiolato ligand) is bonded to iron on the non protected face of the picket fence porphyrin. The displacement of iron out of the 4Np plane is 0.42 Å and appears similar to that in Fe(TPP)(2MeIm) [4]. The Mössbauer data for this compound are similar to others reported [4, 5] and are not very different to those we reported for site (B) [1]. We proposed a distorted six coordinate structure for B shown below:



(B)

However, in the light of the work of Weiss *et al.* [2] it is possible that a preferable structure for B may be E, this site would be five coordinate.



(E)

The results of a comparison of our work with that of Weiss begs the questions, where do the propionate arms of the protoporphyrin IX iron(II) species lie, and, is there a partial cavity caused by them bending over the protoporphyrin IX plane, as we have suggested previously for metal complexes [6, 7].

The protoporphyrin IX five coordinate high spin iron II site with the large quadrupole splitting only

---

*Addressee for correspondence.

0020-1693/84/$3.00

TABLE I. Mössbauer Parameters of Frozen Solutions of protoporphyrin IX Iron(II) Complexes at 80 K.

Ligand	δ mm s^{-1}	Δ mm s^{-1}	Γ mm s^{-1}	% Absn. Area
Phenol	1.04(2)	4.29(2)	0.15(2)	100(2)
Catechol	1.01(2)	4.17(2)	0.15(2)	100(4)
F$^-$	1.03(2)	4.11(2)	0.19(2)	100(5)
Acetone +	0.56(2)	1.43(2)	0.20(2)	66(2)
triphenylphosphine	1.02(2)	4.41(3)	0.25(3)	34(3)
Acetone	0.60(3)	1.42(1)	0.28(1)	90(2)
	1.02(4)	4.34(7)	0.28(6)	10(2)

occurs at high pH [1]. As the Mössbauer parameters for this site were no usual for porphyrin iron(II) compounds, we have extended our studies at high pH on solutions containing other ligands.

We report here Mössbauer and electronic spectroscopic studies of high pH solutions containing fluorine, catechol, phenol, acetone and triphenylphosphorus as ligands.

Experimental

Preparation of ^{57}iron–PPIX Complexes in Solution for Mössbauer Experiments

5 mg of enriched ^{57}Fe–PPIX prepared according to the method of Caughey [8] was dissolved in 3 ml 25% $(CH_3)_4NOH$ solution.

The solution was centrifuged to remove the insoluble particles. The solution was then put under an N_2 atmosphere. A few drops of concentrated sodium dithionite were then added to the solution. Finally an excess of ligand was added to the solution.

The only ligand that was insoluble in water was triphenylphosphine; this was first dissolved in acetone, before being added to the ^{57}Fe–PPIX solution.

Electronic Absorption Experiments

2 mg hematin (Sigma) were dissolved in 2.5 ml 0.5 N $(CH_3)_4NOH$ and then diluted to 50 ml with 25% $(CH_3)_4NOH$. A few drops of concentrated sodium dithionite solution were added. The spectra were taken after the ligands were added to the solution at high pH.

Instrumentation

Electronic spectra were recorded on a Beckman DU 7 spectrophotometer in 1 cm^2 cells. The Mössbauer spectra were recorded on an instrument previously described [9]. The source was ^{57}Co (10 mCi) in rhodium (Radiochemical Centre, Amersham), at 20 °C. The spectrometer was operated in a saw tooth mode and the spectra computer fitted. The spectrometer was calibrated with a 25 μM thick natural iron reference absorber. All isomer shifts are referred to this as zero shift.

TABLE II. Electronic Spectra of Protoporphyrin IX Iron(II) Complexes at Room Temperature (20 °C).

Ligand	λ_1	λ_2	λ_3
Phenol	436.0	556.5	591
Catechol	433.5	555.5	589.5
F$^-$	433.5	555.5	589.5
Acetone	432	558.0	589.5
Acetone + triphenylphosphine	432	555.5	589

Results and Discussion

The Mössbauer data for the systems reported here appear in Table I. All the data are consistent with high spin iron(II) five coordinate environments as first postulated earlier [1] using a comparison with the Mössbauer parameters for high spin five coordinate iron(II) environments [10–15] such as those of iron(II) bis(dithiocarbamates), and confirmed by the work of Weiss *et al.* [2].

It is worth noting that although we tried other strong field ligands (Table II) containing nitrogen as the axial dentate group (and even CO and CN) these would not give high spin iron(II) environments even at very high pH [16].

As can be seen from Table I a mixture containing acetone and triphenylphosphine gave the largest quadrupole splitting so far found for a high spin iron(II) porphyrin compound [1, 2].

It is possible that it is the acetone that is acting as the ligand rather than the triphenylphosphine as seen from the data in the absence of the latter ligand.

In both systems containing acetone only a small amount of the protoporphyrin IX iron(II) was converted to the high spin five coordinate environment. This is similar to the case for hydroxide previously reported [1], but different from the cases of fluoride, phenol or catechol where total conversion was achieved (Fig. 1).

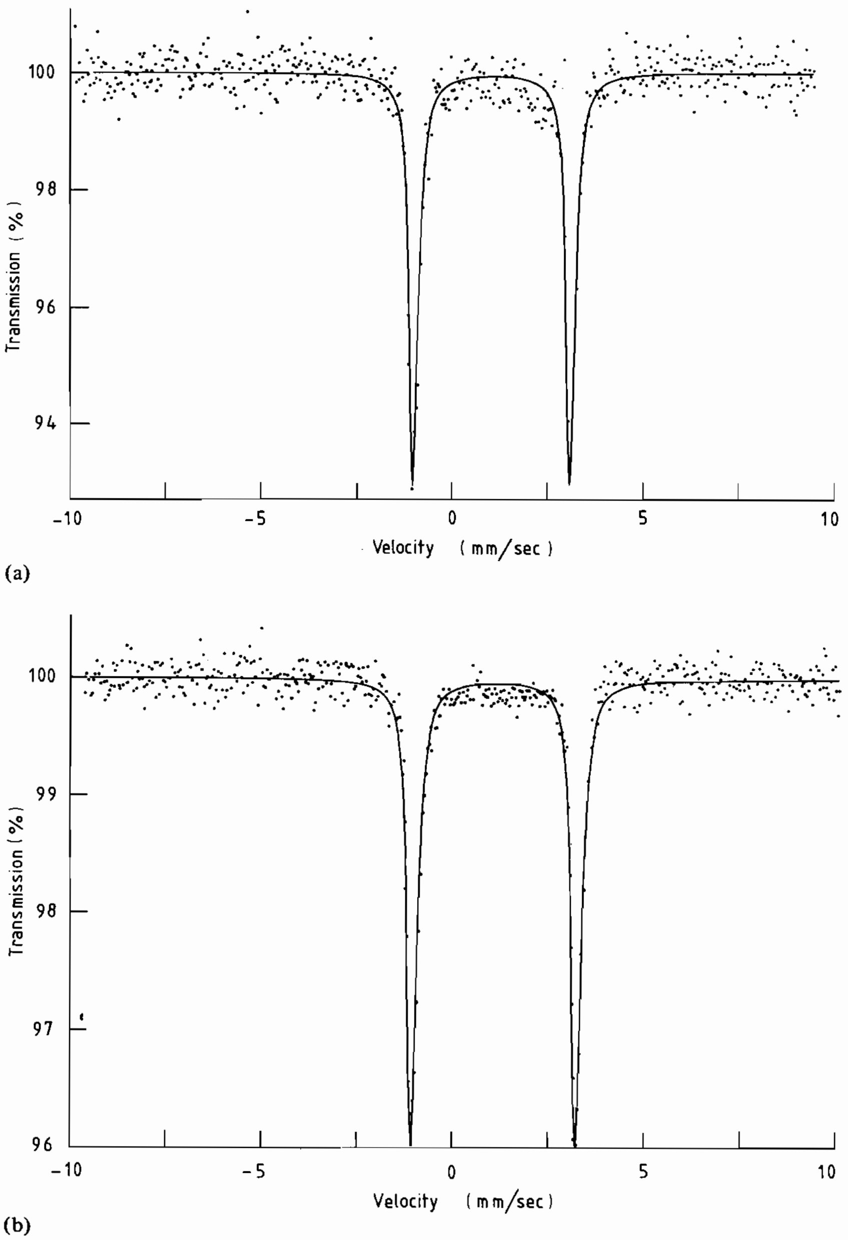


Fig. 1. Mössbauer spectra of protoporphyrin IX iron(II) high spin five coordinate complexes. (a) catechol as fifth ligand; (b) phenol as fifth ligand.

The order of the quadrupole splitting data appears to be:

OH[1] $\approx$ F $<$ catechol $<$ phenol $<$ acetone.

It is not obvious why the order should be as above, but may reflect some aspect of the binding power and geometry of the ligand.

The electronic spectra (Table II, Fig. 2) for the complexes are all nearly identical to that for the protoporphyrin IX iron(II) solutions without ligand present at very high pH (see Table III, ref. [1]). For the solutions where catechol and phenol are present solely in the high quadrupole splitting site (see Mössbauer discussion) only three bands are observed in the electronic spectra. So we suggest that the general form of these electronic spectra is typical of these five coordinate protoporphyrin IX iron(II) systems that display Mössbauer quadrupole splitting of ~4.0 to 4.4 mm s^{-1}.

Obviously as the same electronic spectra are present irrespective of a fifth ligand these spectra must arise predominantly from the protoporphyrin ring and out of plane iron(II) ion with at most only a small contribution from the fifth ligand.

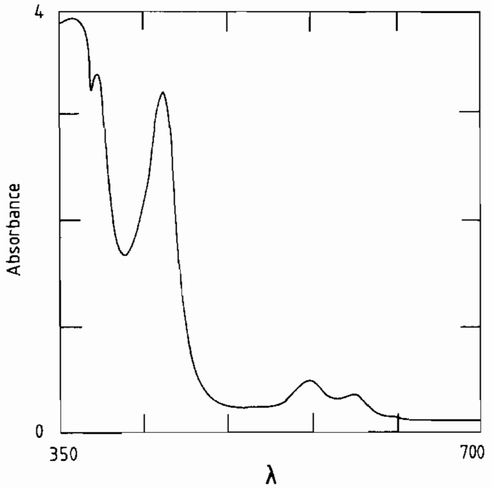


Fig. 2. Electronic absorption spectra of a protoporphyrin IX iron(II) solution containing phenol at pH 14.5.

These are the first protoporphyrin IX iron(II) complexes reported for phenol and catechol, no binding of these ligands is found at lower pH. We have bound protoporphyrin IX iron(III) to phenols and catechols [16] but only at below pH 8, other workers have reported similar data for (FePPIXDME)-($OC_6H_4NO_2$) [17].

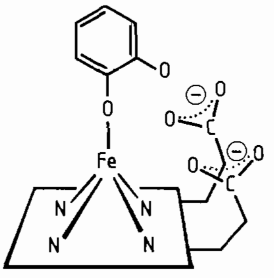
We have also shown that phenolic and catecholic solutions are capable of reducing Fe^{3+} at low pH's [18–20]. Wilson [21] has reported kinetics for the reduction of cytochrome *c* by catechol(s) and related compounds.

As yet we have not been able to reduce protoporphyrin IX iron(III) using catecholic or phenolic solutions and have always needed sodium dithionite present to reduce the protoporphyrin IX iron(III) prior to complexation at high pH. This is, of course, because at high pH protoporphyrin IX iron(III) exists as a μ-OXO oligomer [22] the half wave potential is about –0.48 volts [23] at pH 12.8.

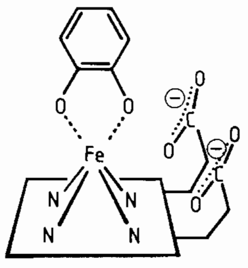
From the similarity of our results to those for $[(Fe(TP_{piv}P)Cl]^-$ $[kC222]C_6H_5Cl$ [2] it is likely that in these materials the two propionate acid arms of the protoporphyrin XI moiety form a half cavity in which the fifth ligand sits. From models all the ligands studied here could manage this though for catechol it depends on whether this ligand binds as in I or in II.

In I free rotation around the Fe–O bond may cause repulsion of the propionate groups by the catechol ligand. In our opinion structure II is less likely to cause such repulsion. There may be some long range attraction of the propionate groups by the Fe(II) ion although the distance of these groups from the Fe is about 4.0 Å.

Such binding of catecholic and phenolic ligands to porphyrins as discussed here has interesting physiological implications. Under normal conditions in the body, can adrenalin and dopamine type molecules bind to protoporphyrin IX iron II/III groups? Is it possible that protoporphyrin IX iron groups are present on adrenergic receptors and could a movement of about 0.6 Å [2] of the Fe atom out of the plane play a role in the binding and unbinding of adrenalin based drugs?



I



II

References

1 J. Silver and B. Lukas, *Inorg. Chim. Acta* (in press).
2 M. Schappacher, L. R. R. Weiss, R. Montiel-Montoya, U. Gonser, E. Bill and A. Trautwein, *Inorg. Chim. Acta, 78,* L9 (1983).
3 M. H. Perutz, J. Serman Hasnain, P. J. Duke, J. L. Sessler and H. E. Hahan, *Nature, 295,* 535 (1982).
4 J. P. Collman, R. R. Gagore, C. A. Reed, T. R. Halbert, G. Lang and W. T. Robinson, *J. Am. Chem. Soc., 97,* 1427 (1975).
5 G. Lang and W. Marshall, *Proc. Phys. Soc. 87,* 3 (1966).
6 B. Lukas, J. R. Miller, J. Silver, M. T. Wilson and I. E. G. Morrison, *J. Chem. Soc. Dalton Trans.,* 1035 (1982).
7 B. Lukas, J. Silver, I. E. G. Morrison and P. W. C. Barnard, *Inorg. Chim. Acta, 78,* 205 (1983).
8 G. Lang and W. Marshall, *Proc. Phys. Soc., 87,* 3 (1966).
9 M. Y. Hamed, R. C. Hider and J. Silver, *Inorg. Chim. Acta, 66,* 13 (1982).
10 J. L. K. F. de Vries, C. P. Keijzers and E. de Boer, *Inorg. Chem. 11,* 1343 (1972).
11 E. Koenig, C. Ritter, E. Lindner and I. P. Lorenz, *Chem. Phys. Lett., 13,* 70 (1972).
12 J. F. Larkworthy, B. W. Fitzsimmons and R. R. Patel, *J. Chem. Soc. Chem. Comm.,* 902 (1973).
13 W. M. Reiff, *Inorg. Chem., 13,* 239 (1974).
14 D. P. Riley, P. H. Merrell, J. A. Stone and D. H. Busch, *Inorg. Chem., 14,* 490 (1975).
15 B. W. Fitzsimmons, S. E. Al-Mukhtar, R. R. Patel, L. F. Larkworthy, *J. Chem. Soc. Dalton Trans.,* 1969 (1975).
16 B. Lukas and J. Silver, unpublished results.
17 S. C. Tang, S. Koch, G. C. Papaefthymiou, S. Foner, R. B. Frankel, James A. Ibers and R. H. Holm, *J. Am. Chem. Soc., 98,* 2414 (1976).
18 J. Silver, I. E. G. Morrison and L. V. C. Rees, *Inorg. Nucl. Lett., 15,* 433 (1979).
19 R. C. Hider, J. Silver, J. B. Nielands, I. E. G. Morrison and L. V. C. Rees, *FEBS Lett., 102,* 325 (1979).
20 R. C. Hider, A. R. Mohd-Nor, J. Silver, I. E. G. Morrison and L. V. C. Rees, *J. Chem. Soc. Dalton Trans.,* 609 (1981).
21 M. M. M. Saleem and M. T. Wilson, *Biochem. Jounnal, 201,* 433 (1982).
22 J. Silver and B. Lukas, *Inorg. Chim. Acta, 78,* 219 (1983).
23 T. M. Bednarski and J. Jordan, *J. Am. Chem. Soc., 89,* 1552 (1967).