

# Crystal structure and photolysis spin-trapping EPR investigations of aqua(2-methoxycarbonylethyl)cobaloxime and its $\beta$ -cyclodextrin inclusion complex †

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Aqua(2-methoxycarbonylethyl)cobaloxime **1** and its  $\beta$ -cyclodextrin inclusion complex **2** were synthesized and characterized by <sup>1</sup>H NMR and X-ray crystallography. Structural and conformational comparisons between the inclusion complex and the guest compound are made. The rearrangement reaction of the methoxycarbonylethyl radical was observed in the anaerobic photolysis of aqua(2-methoxycarbonylethyl)cobaloxime in the absence and presence of  $\beta$ -cyclodextrin by using the EPR spin-trapping technique. The changes of EPR parameters indicate that the formed spin adduct could be included in the  $\beta$ -cyclodextrin's cavity.

Alkylcobaloximes have been extensively employed as models for the naturally occurring coenzyme B<sub>12</sub>, which serves as a cofactor for many enzymatic reactions.<sup>1,2</sup> A common feature of these reactions is that a hydrogen atom interchanges with a substituent on the adjacent carbon atom of the substrate. Homolysis of the Co–C bond of coenzyme B<sub>12</sub> to product 5'-deoxyadenosyl radicals is generally accepted as the key step in these reactions.<sup>3–5</sup> Many investigations have been undertaken to study the photo-induced homolysis of Co–C bonds in the coenzyme B<sub>12</sub> model compounds for they might simulate the behavior of either the 5'-deoxyadenosyl radical released in the enzymatic reactions or the radical intermediates between substrate and product.<sup>6</sup> Recently, Breslow *et al.*<sup>7</sup> prepared a cyclodextrin-bound B<sub>12</sub> as a enzyme model, in which cobalamin is directly linked to the primary carbon of  $\beta$ -cyclodextrin. Cyclodextrins (CDs) are a class of cyclic oligosaccharide molecules normally comprised of six( $\alpha$ ), seven( $\beta$ ) or eight( $\gamma$ )  $\alpha$ -(1 $\rightarrow$ 4) linked D(+)-glucopyranose units, with a toroidal hydrophobic cavity capable of including a variety of inorganic and organic guest species to form rather stable compounds.<sup>8–11</sup> The inclusion phenomena of cyclodextrin have been studied extensively as models for enzyme–substrate interactions. In our previous work, a series of alkylcobaloxime–cyclodextrin [CoR(HD)<sub>2</sub>(H<sub>2</sub>O)]–CD, R = *n*-C<sub>3</sub>H<sub>7</sub>, *n*-C<sub>4</sub>H<sub>9</sub>, *n*-C<sub>5</sub>H<sub>11</sub>, *i*-C<sub>4</sub>H<sub>9</sub>, *c*-C<sub>6</sub>H<sub>11</sub>, *etc.*; H<sub>2</sub>D = dimethylglyoxime; CD =  $\alpha$ - or  $\beta$ -cyclodextrin) inclusion complexes were synthesized and characterized.<sup>12,13</sup> Among them, the crystal structure of [Co(*n*-C<sub>3</sub>H<sub>7</sub>)(HD)<sub>2</sub>(H<sub>2</sub>O)]– $\alpha$ -CD has been reported.<sup>13</sup> Since alkoxy-carbonylcobaloximes are often used to model coenzyme B<sub>12</sub> catalysed rearrangement,<sup>14</sup> we wanted to prepare alkoxy-carbonylcobaloxime–CD inclusion complexes for structural and photolysis investigation. Here we report a new structure of an aqua(2-methoxycarbonylethyl)cobaloxime– $\beta$ -CD inclusion complex. For comparison, the structure of the guest compound aqua(2-methoxycarbonylethyl)cobaloxime was also deter-

mined. The EPR spin-trapping technique was used to investigate the short-lived free radicals which were formed in the anaerobic photolysis of aqua(2-methoxycarbonylethyl)cobaloxime with the radical trap of 2-methyl-2-nitrosopropane (MNP) in the absence and presence of  $\beta$ -CD.

## Experimental

All chemicals were A.R. or C.P. grade;  $\beta$ -CD was supplied by Nanjing Food Ferment Institute, recrystallized twice from distilled water and dried *in vacuo* at 80 °C before use.

## Preparations

**[Co(CH<sub>2</sub>CH<sub>2</sub>O<sub>2</sub>CCH<sub>3</sub>)(HD)<sub>2</sub>(H<sub>2</sub>O)] 1.** This was prepared by the method of Schrauzer and Windgassen,<sup>15</sup> yield 40% (Found: C, 36.4; H, 5.5; N, 13.8. Calc. for C<sub>12</sub>H<sub>23</sub>CoN<sub>4</sub>O<sub>7</sub>: C, 36.56; H, 5.88; N, 14.21%). <sup>1</sup>H NMR (500 MHz, D<sub>2</sub>O): for 2-methoxycarbonylethyl group,  $\delta$  1.70 (2 H, t, CH<sub>2</sub>), 1.77 (2 H, t, CH<sub>2</sub>) and 3.61 (3 H, s, CO<sub>2</sub>CH<sub>3</sub>); for Co(HD)<sub>2</sub>,  $\delta$  2.25 (12 H, s, CH<sub>3</sub>). A single crystal of 1·0.5H<sub>2</sub>O suitable for X-ray analysis was obtained by recrystallization from water–methanol solution.

**[Co(CH<sub>2</sub>CH<sub>2</sub>O<sub>2</sub>CCH<sub>3</sub>)(HD)<sub>2</sub>(H<sub>2</sub>O)]– $\beta$ -CD 2.** The  $\beta$ -CD inclusion complex was synthesized by the following procedure. A 1:1 molar ratio of **1** and  $\beta$ -CD was dissolved in water by constant stirring for 30 min at 50 °C. The resulting solution was filtered and the filtrate stored at 25 °C in the dark. One week later orange crystals of 2·9H<sub>2</sub>O were obtained (yield 60%) (Found: C, 40.5; H, 6.4; N, 3.3. C<sub>54</sub>H<sub>101</sub>CoN<sub>4</sub>O<sub>46</sub> requires C, 40.49; H, 6.36; N, 3.50%). The crystals were easy to crack upon dehydration. <sup>1</sup>H NMR (500 MHz, D<sub>2</sub>O at concentration of 3.6 × 10<sup>–3</sup> mol dm<sup>–3</sup>) for 2-methoxycarbonylethyl group,  $\delta$  1.72 (2 H, t, CH<sub>2</sub>), 1.78 (2 H, t, CH<sub>2</sub>) and 3.59 (3 H, m, CO<sub>2</sub>CH<sub>3</sub>); for Co(HD)<sub>2</sub>,  $\delta$  2.28 (12 H, d, CH<sub>3</sub>); for  $\beta$ -CD,  $\delta$  3.59 (7 H, m, H-4), 3.65 (7 H, dd, H-2), 3.84 (7 H, m, H-5), 3.87 (14 H, d, H-6), 3.94 (7 H, t, H) and 5.07 (7 H, d, H-1). These data show that: (a) the resonances of protons of the 2-methoxycarbonylethyl ligand shift to different extents; (b) the chemical shifts of the methyl group of the equatorial ligand move downfield and the singlet

† Supplementary data available: EPR spectra. Available from BLDSC (No. SUP 57476, 3 pp.). See Instructions for Authors, 1999, Issue 1 (<http://www.rsc.org/dalton>).

resonance splits into a doublet; (c) from the integrated signal areas, the molar ratio of complex to  $\beta$ -CD is 1 : 1. These suggest that the inclusion complex was formed in aqueous solution.

Further, based on the fact that the chemical shifts observed differ with changing concentration of 1:1 adduct,  $^1\text{H}$  NMR spectroscopy was used quantitatively to determine the formation constant of the inclusion complex.<sup>12,13</sup> The log  $K_f$  value for  $[\text{Co}(\text{CH}_2\text{CH}_2\text{O}_2\text{CCH}_3)(\text{HD})_2(\text{H}_2\text{O})]-\beta\text{-CD}$  is 3.49.

### Crystallography

The crystal structures of  $[\text{Co}(\text{CH}_2\text{CH}_2\text{O}_2\text{CCH}_3)(\text{HD})_2(\text{H}_2\text{O})]\cdot 0.5\text{H}_2\text{O}$  and  $[\text{Co}(\text{CH}_2\text{CH}_2\text{O}_2\text{CCH}_3)(\text{HD})_2(\text{H}_2\text{O})]-\beta\text{-CD}\cdot 9\text{H}_2\text{O}$  were determined. Raw intensities for complex **1** $\cdot 0.5\text{H}_2\text{O}$  were collected using a Siemens P4 four-circle diffractometer with monochromated Mo-K $\alpha$  ( $\lambda = 0.71073$ ) radiation and a  $\omega$ - $2\theta$  scan mode with variable scan speed of 4.0–40.0°  $\omega$  min<sup>-1</sup>. The data were corrected for Lorentz-polarization effects during data reduction using XSCANS.<sup>16</sup> The intensities for **2** $\cdot 9\text{H}_2\text{O}$  were collected on a Rigaku RAXIS-IIS imaging-plate system with a rotating-anode X-ray source (50 kV, 90 mA). The structures of both compounds were solved by direct methods using the SHELXTL PC<sup>17</sup> program package and refinement (based on  $F^2$ ) by full-matrix least squares. The hydrogen atoms attached to the carbons of the ligands were placed in calculated positions (C–H 0.96 Å), assigned fixed isotropic thermal parameters, and allowed to ride on their respective parent atoms.

CCDC reference number 186/1276.

### EPR experiment

The EPR measurements were carried out on a JEOL-FE1XG spectrometer at room temperature with 100 kHz field modulation, 0.5 G modulation width, 5 mW microwave power and 9.45 GHz microwave frequency, 0.1 s response time. Irradiation was performed in the cavity of the EPR spectrometer by a BM-501S high pressure mercury lamp with wavelength in the ultraviolet range. Samples were prepared under dim red lights and injected into a flat quartz sample tube (0.5  $\times$  4.2  $\times$  43.5 mm). The aqueous solution without  $\beta$ -CD contained  $2 \times 10^{-2}$  mol dm<sup>-3</sup> **1** and  $6 \times 10^{-2}$  mol dm<sup>-3</sup> MNP, which was prepared by adding 25 mg MNP in 5 cm<sup>-3</sup> redistilled water with continuous stirring for 4 h at 45 °C under nitrogen. The sample in the presence of  $\beta$ -CD contained  $1 \times 10^{-3}$  mol dm<sup>-3</sup> **2** solution,  $2 \times 10^{-2}$  mol dm<sup>-3</sup> MNP aqueous solution and  $2 \times 10^{-2}$  mol dm<sup>-3</sup>  $\beta$ -CD. EPR Spectral simulations were made by the program of Oehler and Janzen.<sup>18</sup>

## Results and discussion

### Crystal structure

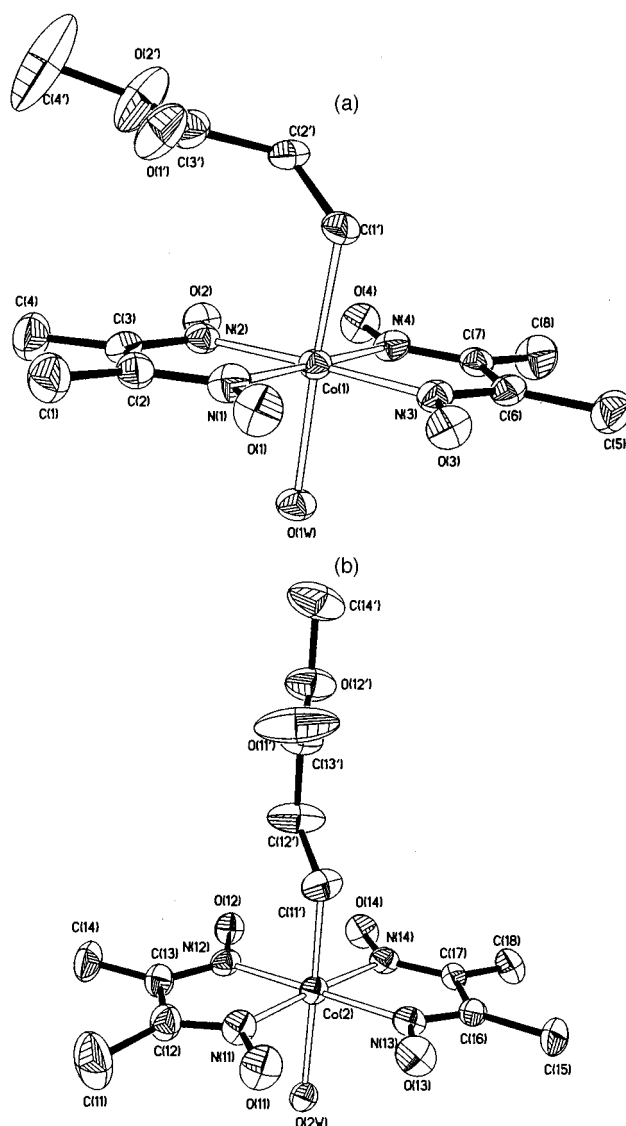
Crystallographic data for complexes **1** $\cdot 0.5\text{H}_2\text{O}$  and **2** $\cdot 9\text{H}_2\text{O}$  are listed in Table 1.

**Complex 1** $\cdot 0.5\text{H}_2\text{O}$ . It is noteworthy that there are two crystallographically independent molecules in the asymmetric unit of complex **1** $\cdot 0.5\text{H}_2\text{O}$ . The numbering schemes are shown in Fig. 1, and bond lengths and angles are reported in Table 2. The two crystallographically independent molecules, **1a** and **1b**, each have four nitrogen atoms of the HD unit coplanar within  $\pm 0.020$  and  $\pm 0.010$  Å respectively. The cobalt atoms Co(1) and Co(2) are displaced by 0.011 and 0.024 Å respectively above the respective mean planes towards the alkyl group. The two HD units are slightly bent away from the alkyl group, making a dihedral angle of 3 and 6° respectively. The H<sub>2</sub>O–Co–R fragments are characterized by O–Co–C angles of 176.4(2) and 177.7(3)°, Co–C bond lengths of 2.000(6) and 1.987(7) Å, and Co–O bond lengths of 2.069(4) and 2.070(4) Å respectively.

It is interesting that the 2-methoxycarbonyl ethyl group exhibits different spacial orientations in molecules **1a** and **1b**,

**Table 1** Crystallographic data for complexes **1** $\cdot 0.5\text{H}_2\text{O}$  and **2** $\cdot 9\text{H}_2\text{O}$

	<b>1</b> $\cdot 0.5\text{H}_2\text{O}$	<b>2</b> $\cdot 9\text{H}_2\text{O}$
Formula	C <sub>12</sub> H <sub>23</sub> CoN <sub>4</sub> O <sub>7</sub> $\cdot 0.5\text{H}_2\text{O}$	C <sub>54</sub> H <sub>93</sub> CoN <sub>4</sub> O <sub>42</sub> $\cdot 9\text{H}_2\text{O}$
<i>M</i>	403.28	1691.40
<i>T</i> /K	293(2)	295(2)
Crystal system	Triclinic	Orthorhombic
Space group	<i>P</i> $\bar{1}$	<i>P</i> 2 <sub>1</sub> 2 <sub>1</sub> 2 <sub>1</sub>
<i>a</i> /Å	11.583(2)	15.1760(3)
<i>b</i> /Å	11.627(3)	18.9710(6)
<i>c</i> /Å	14.661(4)	28.0200(10)
<i>a</i> /°	69.97(5)	
<i>b</i> /°	80.37(4)	
<i>c</i> /°	80.13(3)	
<i>U</i> /Å <sup>3</sup>	1815.1(7)	8067.1(4)
<i>Z</i>	4	4
$\mu$ /mm <sup>-1</sup>	0.988	0.319
Reflections collected	6631	23933
Independent reflections	6293	13293
<i>R</i> <sub>int</sub>	0.0434	0.0716
Final <i>R</i> 1, <i>wR</i> 2 [ <i>I</i> > 2 $\sigma$ ( <i>I</i> )]	0.0667, 0.1751	0.0812, 0.2103

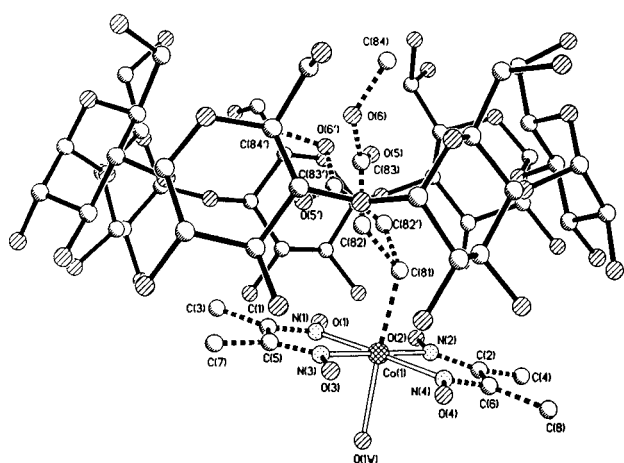


**Fig. 1** Structure and numbering schemes of  $[\text{Co}(\text{CH}_2\text{CH}_2\text{O}_2\text{CCH}_3)(\text{HD})_2(\text{H}_2\text{O})]$  in complex **1** $\cdot 0.5\text{H}_2\text{O}$ : (a) molecule **1a**, (b) molecule **1b**.

which could be characterized by the torsion angles of Co(1)–C(1')–C(2')–C(3') (84.9°) and Co(2)–C(11')–C(12')–C(13') (177.3°). That is, this group of **1a** is almost parallel to the

**Table 2** Selected bond lengths (Å) and angles (°) for complex 1

Co(1)–N(1)	1.884(5)	Co(1)–N(2)	1.888(5)
Co(1)–N(3)	1.884(5)	Co(1)–N(4)	1.883(5)
Co(1)–C(1')	2.000(6)	Co(1)–O(1W)	2.069(4)
C(1')–C(2')	1.509(9)	C(2')–C(3')	1.519(10)
C(3')–O(1')	1.190(9)	C(3')–O(2')	1.303(9)
C(4')–O(2')	1.504(12)	Co(2)–N(12)	1.877(5)
Co(2)–N(11)	1.878(5)	Co(2)–N(13)	1.887(5)
Co(2)–N(14)	1.891(5)	Co(2)–C(11')	1.987(7)
Co(2)–O(2W)	2.070(4)	C(11')–C(12')	1.431(10)
C(12')–C(13')	1.492(10)	C(13')–O(11')	1.169(9)
C(13')–O(12')	1.296(8)	C(14')–O(12')	1.460(11)
N(1)–Co(1)–C(1')	90.6(3)	N(2)–Co(1)–C(1')	95.0(2)
N(3)–Co(1)–C(1')	86.8(2)	N(4)–Co(1)–C(1')	88.7(3)
N(1)–Co(1)–O(1W)	89.3(2)	N(2)–Co(1)–O(1W)	88.6(2)
N(3)–Co(1)–O(1W)	89.6(2)	N(4)–Co(1)–O(1W)	91.4(2)
C(1')–Co(1)–O(1W)	176.4(2)	C(2')–C(1')–Co(1)	118.1(5)
C(1')–C(2')–C(3')	114.8(6)	O(1')–C(3')–O(2')	125.5(8)
O(1')–C(3')–C(2')	123.2(7)	O(2')–C(3')–C(2')	111.2(7)
C(3')–O(2')–C(4')	115.2(8)	N(11)–Co(2)–C(11')	90.1(3)
N(12)–Co(2)–C(11')	92.8(3)	N(13)–Co(2)–C(11')	88.2(3)
N(14)–Co(2)–C(11')	92.0(3)	N(11)–Co(2)–O(2W)	87.7(2)
N(12)–Co(2)–O(2W)	87.5(2)	N(13)–Co(2)–O(2W)	91.6(2)
N(14)–Co(2)–O(2W)	90.2(2)	C(11')–Co(2)–O(2W)	177.7(3)
C(12')–C(11')–Co(2)	120.4(5)	C(11')–C(12')–C(13')	116.0(7)
O(11')–C(13')–O(12')	122.1(7)	O(11')–C(13')–C(12')	125.7(7)
O(12')–C(13')–C(12')	112.2(7)	C(13')–O(12')–C(14')	117.1(7)

**Fig. 2** Structure of  $[\text{Co}(\text{CH}_2\text{CH}_2\text{O}_2\text{CCH}_3)(\text{HD})_2(\text{H}_2\text{O})]-\beta\text{-CD}$  in complex  $2\cdot 9\text{H}_2\text{O}$ .

$\text{Co}(\text{HD})_2$  unit, while in **1b** it is almost vertical. This is probably related to the packing of the molecules in the crystal.

**Complex  $2\cdot 9\text{H}_2\text{O}$ .** The structure of the molecule is depicted in Fig. 2. Selected bond lengths and angles are given in Table 3. The lattice water molecules link the host–guest complexes into a three dimensional network. As can be seen in Fig. 2, the 2-methoxycarbonylethyl group of the guest inserts into the cavity of  $\beta\text{-CD}$  from its wider opening [the atoms of C(81), C(84) and C(84') are above the mean plane of O atoms associated with fourteen secondary OH groups by 0.2, 4.9 and 3.5 Å respectively]. It also exhibits orientational disorder, which arises from a rotation about the C(81)–C(82) bond. The guest molecule apparently strives to fill up the cyclodextrin cavity.<sup>19</sup>

In the  $\text{Co}(\text{HD})_2$  unit the four nitrogen atoms are coplanar, the mean deviation from the best plane being 0.014 Å. The cobalt atom lies almost in the mean plane (deviation 0.018 Å). The bending angle for two HD planes is 4°. In the O–Co–R fragment the Co–C and Co–O distances are 1.998(2) and 2.100(1) Å respectively, and the C–Co–O angle is 176.0(1)°.

**Structure comparison.** In the previous reported structure of the  $[\text{Co}(n\text{-C}_3\text{H}_7)(\text{HD})_2(\text{H}_2\text{O})]-\alpha\text{-CD}$  inclusion complex,<sup>13</sup> conformational changes of the alkylcobaloxime, such as a large

**Table 3** Selected bond lengths (Å) and angles (°) for complex 2

Co(1)–N(1)	1.879(2)	Co(1)–N(2)	1.874(2)
Co(1)–N(3)	1.900(2)	Co(1)–N(4)	1.892(2)
Co(1)–C(81)	1.998(2)	Co(1)–O(1W)	2.0996(14)
C(81)–C(82)	1.518(4)	C(82)–C(83)	1.523(5)
C(83)–O(5)	1.209(6)	C(83)–O(6)	1.453(5)
C(84)–O(6)	1.469(6)	C(82')–C(83')	1.509(5)
C(83')–O(5')	1.216(5)	C(83')–O(6')	1.421(6)
C(84')–O(6')	1.447(6)		
N(1)–Co(1)–C(81)	92.06(10)	N(2)–Co(1)–C(81)	88.12(9)
N(3)–Co(1)–C(81)	92.18(9)	N(4)–Co(1)–C(81)	89.88(9)
N(1)–Co(1)–O(1W)	91.12(7)	N(2)–Co(1)–O(1W)	88.99(7)
N(3)–Co(1)–O(1W)	90.78(7)	N(4)–Co(1)–O(1W)	86.94(6)
C(81)–Co(1)–O(1W)	175.98(8)	C(82)–C(81)–Co(1)	124.5(2)
C(81)–C(82)–C(83)	120.0(3)	O(5)–C(83)–C(82)	118.1(5)
O(6)–C(83)–C(82)	116.7(4)	O(5)–C(83)–O(6)	125.1(5)
C(83)–O(6)–C(84)	120.6(5)	O(5')–C(83')–C(82')	116.8(5)
O(6')–C(83')–C(82')	111.8(3)	O(5')–C(83')–O(6')	130.6(5)
C(83')–O(6')–C(84')	102.3(5)		

bending angle, Co atom pulled out of the 4N plane towards the alkyl group, *etc.* are found after forming the inclusion complex. Our present X-ray crystallographic investigation reveals that, except for the longer Co–O bond, there is no appreciable difference in the bond length, angle and conformation in the aqua-(2-methoxycarbonylethyl)cobaloxime, in contrast to those in  $[\text{Co}(n\text{-C}_3\text{H}_7)(\text{HD})_2(\text{H}_2\text{O})]-\alpha\text{-CD}$ . It is deduced that the distortions might cause the short alkyl group of  $n\text{-C}_3\text{H}_7$  to insert into the CD cavity more deeply, thereby facilitating stronger van der Waals forces and hydrophobic interaction, which were generally accepted to be responsible for bonding of guest molecules to CD.<sup>20,21</sup> As for our present structure of  $[\text{Co}(\text{CH}_2\text{CH}_2\text{O}_2\text{CCH}_3)(\text{HD})_2(\text{H}_2\text{O})]-\beta\text{-CD}$ , the alkyl group is long enough to go deep into the cavity of CD as mentioned above. So that a rather stable inclusion complex can be formed without conformational change of the  $\text{Co}(\text{HD})_2$  unit.

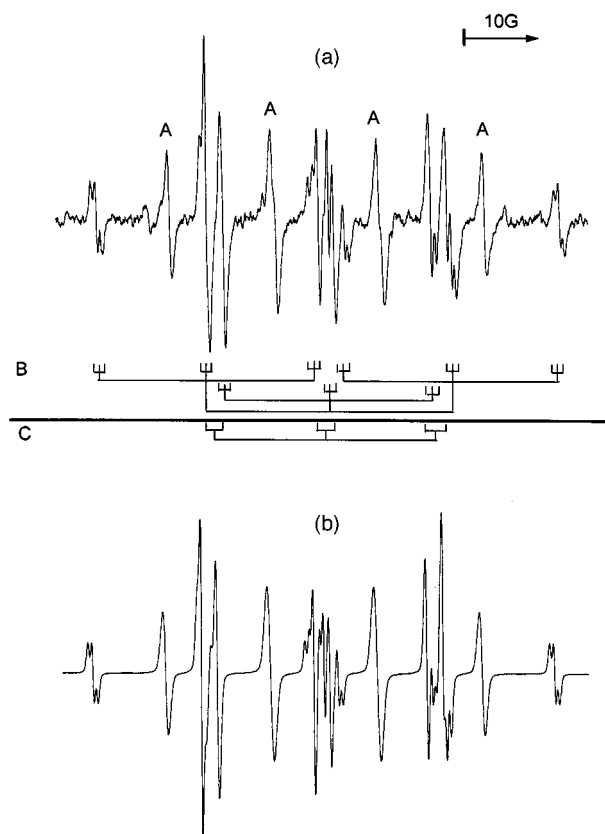
### Photolysis spin-trapping EPR

The photolysis EPR spectrum of aqua(2-methoxycarbonylethyl)cobaloxime with spin trap MNP is shown in Fig. 3(a), comprising three sets of signals A, B and C. Signal A could be ascribed to a H–MNP spin adduct with hyperfine splittings (hfs)  $a_{\text{N}}(1) = 14.4$  G,  $a_{\alpha\text{-H}}(1) = 14.0$  G, consistent with a previous report.<sup>22</sup> Our EPR experiment in  $\text{D}_2\text{O}$  solution (see SUP 57476) indicates that the H atom might come from the solvent. Signal B is due to a  $\text{CH}_3\text{CO}_2(\text{CH}_2)_2\text{-MNP}$  spin adduct with  $a_{\text{N}}(1) = 16.5$  G,  $a_{\beta\text{-H}}(2) = 14.6$  G,  $a_{\gamma\text{-H}}(2) = 0.5$  G. According to the photolysis spin-trapping EPR spectrum of aqua(1-methoxycarbonylethyl)cobaloxime (see SUP 57476), signal C could be assigned to the spin adduct of  $\text{CH}_3\text{CO}_2(\text{CH}_3)\text{CH-MNP}$  with  $a_{\text{N}}(1) = 15.2$  G,  $a_{\beta\text{-H}}(1) = 2.2$  G, which gives some overlapping peaks with signal B. Fig. 3(b) is a computer simulation using the EPR parameters of the three spin adducts. It is clear that most of the spectral features are well reproduced.

In our experiment short-lived alkyl radicals of  $\text{CH}_3\text{CO}_2(\text{CH}_2)_2\cdot$  and  $\text{CH}_3\text{CO}_2(\text{CH}_3)\text{CH}\cdot$  were trapped by MNP. It is suggested that the  $\text{CH}_3\text{CO}_2(\text{CH}_3)\text{CH}\cdot$  radical is formed through a 1,2-proton shift from the precursor  $\text{CH}_3\text{CO}_2(\text{CH}_2)_2\cdot$  radical generated *via* photolysis of  $[\text{Co}(\text{CH}_2\text{CH}_2\text{O}_2\text{CCH}_3)(\text{HD})_2(\text{H}_2\text{O})]$ .

The EPR spectrum obtained on photolysis of complex **2** in the presence of MNP and  $\beta\text{-CD}$  is shown in Fig. 4. All three spin adducts could be detected, which means the rearrangement of the radical still occurred in the presence of  $\beta\text{-CD}$ . The  $a_{\text{N}}$  and  $a_{\text{H}}$  values are given in Table 4.

From previous investigations of spin-trapping EPR using aminoxyl radicals as scavenger it has been found that EPR parameters ( $a_{\text{N}}$ ) are sensitive to the environment.<sup>23,24</sup> The values of nitrogen hfs can reflect the polarity around the aminoxyl



**Fig. 3** The EPR spectrum of the MNP spin adduct: (a) produced in the photolysis of complex **1** at 293 K, scavenger MNP, solvent water; (b) simulation of (a).

group. In apolar media the hfs becomes smaller than in polar media. Comparing the hfs of the aminoxyl radicals with and without  $\beta$ -CD, as can be seen from Table 4, the nitrogen hfs for the three spin adducts become smaller in the presence of  $\beta$ -CD, suggesting that the aminoxyl radicals are in a less polar environment than in pure water; apparently, they are included into the hydrophobic cavities of  $\beta$ -CD. Meanwhile, the line-widths in Fig. 4 are increased compared with those in Fig. 3, especially for the high-field peak, which is due to the restriction of the tumbling motion of the spin adduct inside the cavity of  $\beta$ -CD. This provides further evidence for the formation of the inclusion complex.<sup>25–28</sup>

In short, by using the spin-trapping EPR technique, we have characterized short-lived radicals which arise from the photolysis of aqua(2-methoxycarbonylethyl)cobaloxime and its  $\beta$ -CD inclusion species, and given evidence for a rearrangement reaction from the primary alkyl radical to the secondary one. To our knowledge, though many investigations have been done on the photolytic homolysis of the Co–C bond in coenzyme B<sub>12</sub> and its model compounds,<sup>29–34</sup> there are few reports on the resulting radical rearrangements. Since rearrangements of substrate radicals are involved in the B<sub>12</sub>-dependent enzymatic reaction,<sup>3</sup> the radical rearrangement reaction we report here might have some biochemical implications.

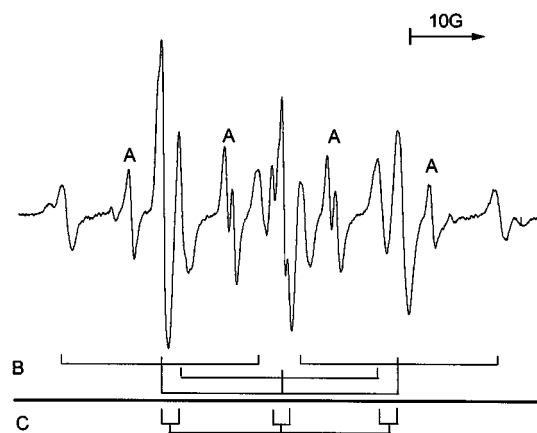
## Conclusion

The crystal structure of aqua(2-methoxycarbonylethyl)cobaloxime contains two independent molecules with different alkyl orientations. Proton NMR and X-ray diffraction studies showed that 2-methoxycarbonylethylcobaloxime forms a 1:1 inclusion complex with  $\beta$ -CD. The conformation change of the Co(HD)<sub>2</sub> unit is small after inclusion, showing that the 2-methoxycarbonylethyl group matches the depth of the  $\beta$ -CD cavity better than the previously reported *n*-C<sub>3</sub>H<sub>7</sub> in  $\alpha$ -CD. A photolysis spin-trapping EPR investigation of 2-methoxy-

**Table 4** The EPR parameters for free and included radicals detected in aqueous media at 293 K

Radical		$a_N/G$	$a_{\alpha-H}/G$	$a_{\beta-H}/G$	$a_{\gamma-H}/G$
A H-MNP	Free	14.4	14.0		
	$\beta$ -CD	14.0	13.0		
B CH <sub>3</sub> CO <sub>2</sub> (CH <sub>2</sub> ) <sub>2</sub> -MNP	Free	16.5		14.6	0.5
	$\beta$ -CD	16.1		13.4	
C CH <sub>3</sub> CO <sub>2</sub> (CH <sub>3</sub> )CH-MNP	Free	15.2		2.2	
	$\beta$ -CD	14.8		2.2	

Error is  $\pm 0.1$  G for  $a_N$  and  $a_H$ .



**Fig. 4** The EPR spectrum of the MNP spin adduct produced in the photolysis of complex **2** at 293 K in the presence of  $\beta$ -CD. Solvent: water.

carbonylethylcobaloxime in the absence and presence of  $\beta$ -CD using MNP as radical trap indicated that the spin adducts could be included in the cavity of  $\beta$ -CD, and the 1,2-proton shift of the alkyl radical was detected.

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